High Power Lasers in Manufacturing

by

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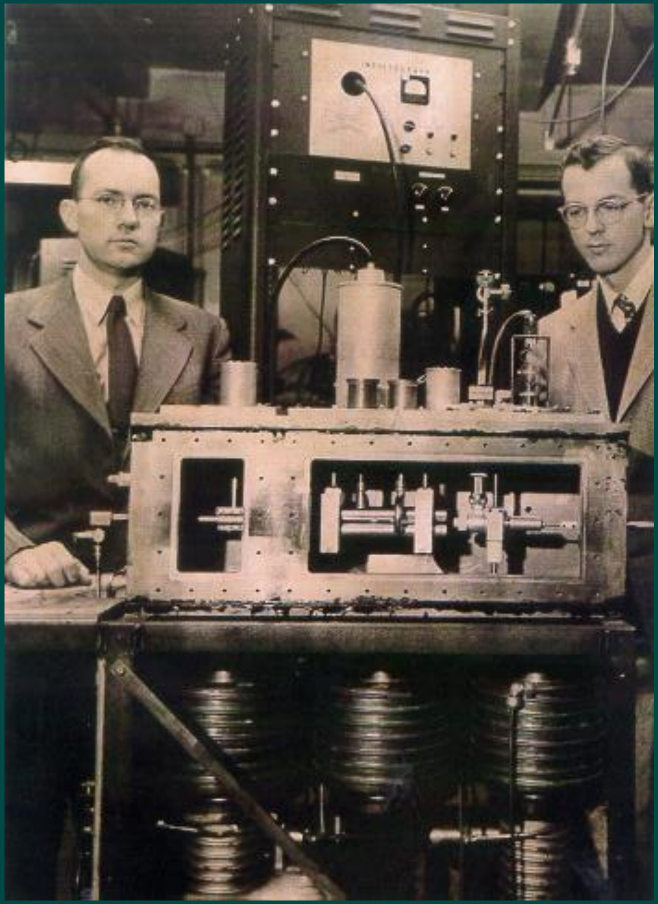
http://www.sussex.ac.uk/profiles/9815

Brief History and Evolution of Lasers

- 1917 - Albert Einstein developed the concept of stimulated emission, which is the phenomenon used in lasers
- In 1954 the maser was the first device to use stimulated emission (Townes & Schawlow). Microwave amplification by stimulated emission of radiation

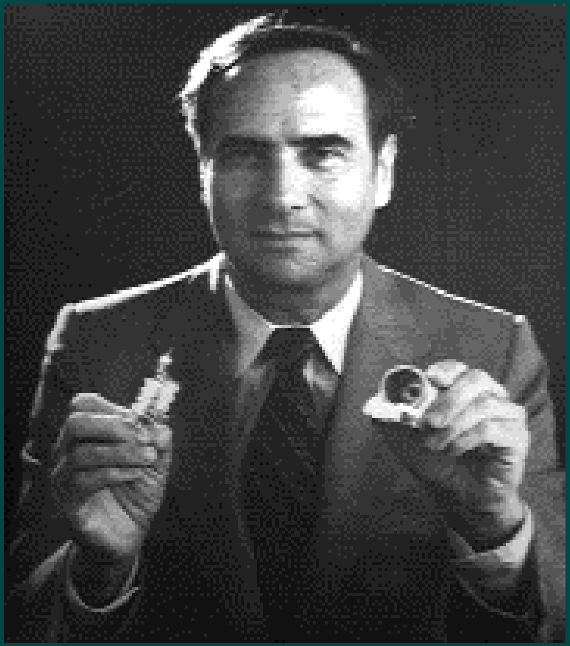
Brief History of Lasers



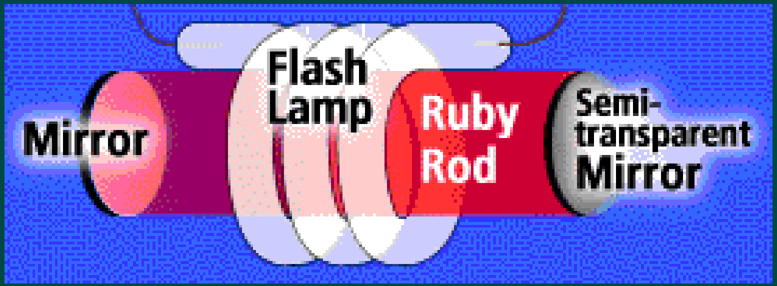
Charles Townes & Jim Gordon at Columbia University in 1954 with their second working MASER

- In 1958 Townes & Schawlow suggested that stimulated emission could be used in the infrared and optical portions of the spectrum
- The device was originally termed the optical maser
- This term was dropped in favour of LASER. Standing for Light Amplification by Stimulated Emission of Radiation

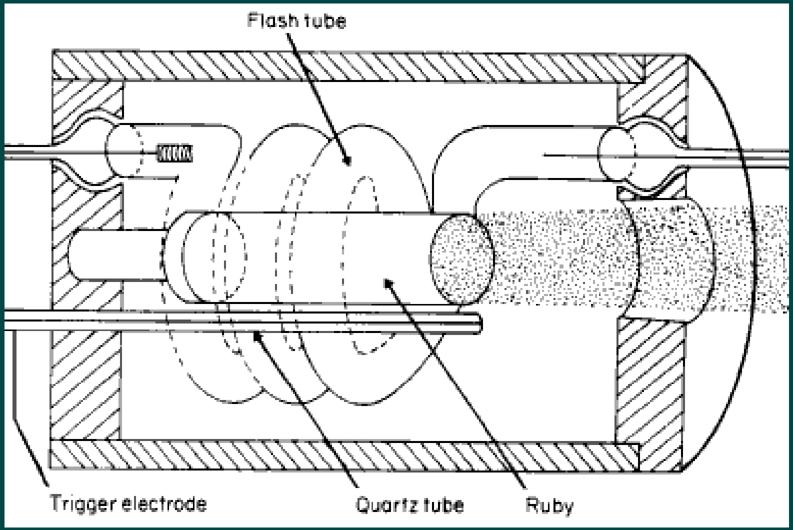
1^{st} Laser - Ted Maiman 15th May 1960 - working alone and against the wishes of his boss at Hughes Research Laboratories



Electrical Engineer



Maiman’s Ruby Laser - 694.3 nm



New York Times
8th July 1960,
Wrong Ruby Crystal
is shown here.
The journalist didn’t
like the actual stubby
crystal. This crystal
was used later

Synthetic pale pink ruby crystal Al_2O_3
containing about 0.05% by weight of Cr_2O_3

Bell Labs & the Laser

1960 Ali Javan, William Bennet, Donald Herriot - HeNe Laser - 1st CW Laser - 1.15 μm

1961 Boyle & Nelson - Continuously operating Ruby Laser

1962 Kumar Patel (front), Faust, McFarlane, Bennet (left to right) - 5 Noble gas lasers and lasers using oxygen mixtures

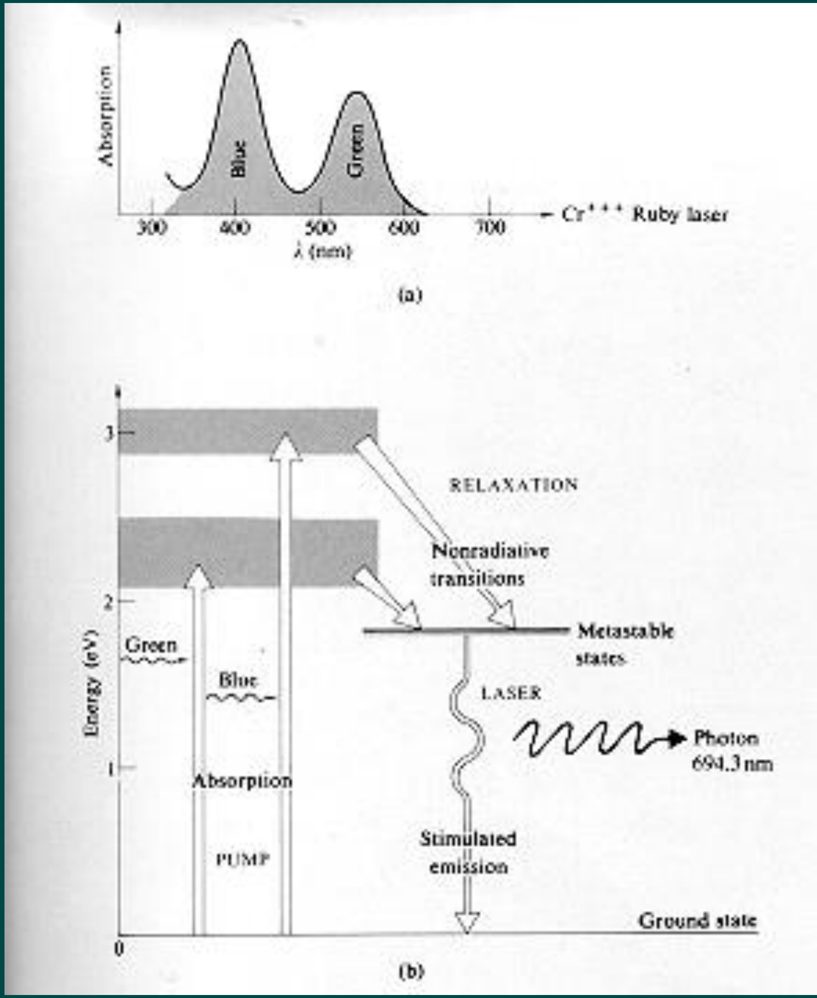
Bell Labs & the Laser

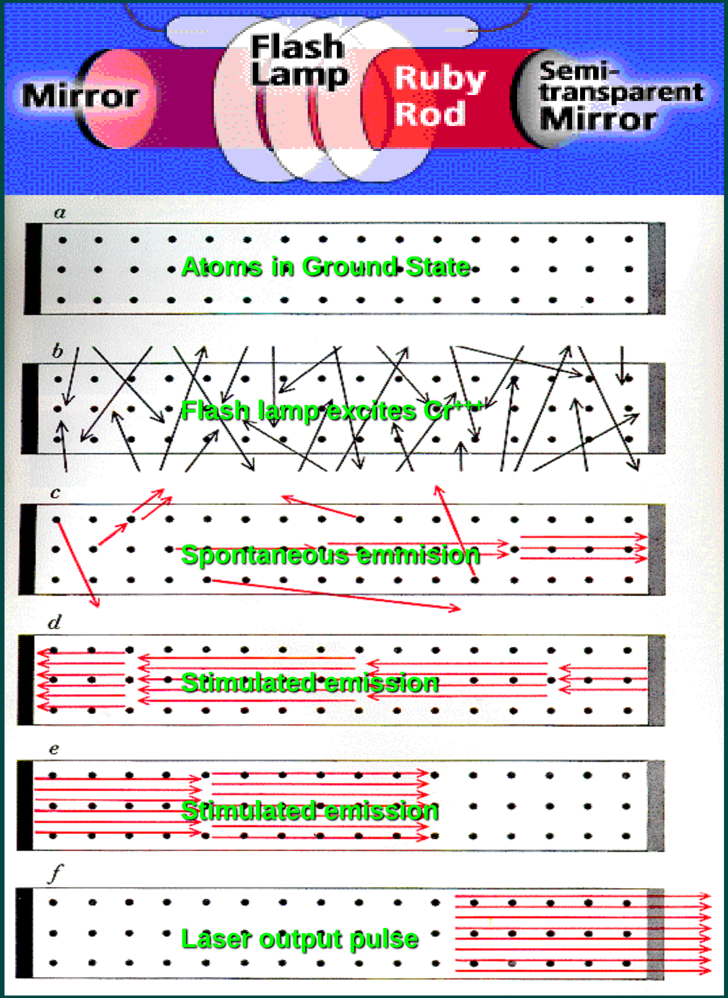
1964 C. K. N. Patel - High Power Carbon Dioxide Laser - 10.6μm

1971 Izuo Hayashsi & Morton Panish - first semiconductor laser that operated continuously at room temperature

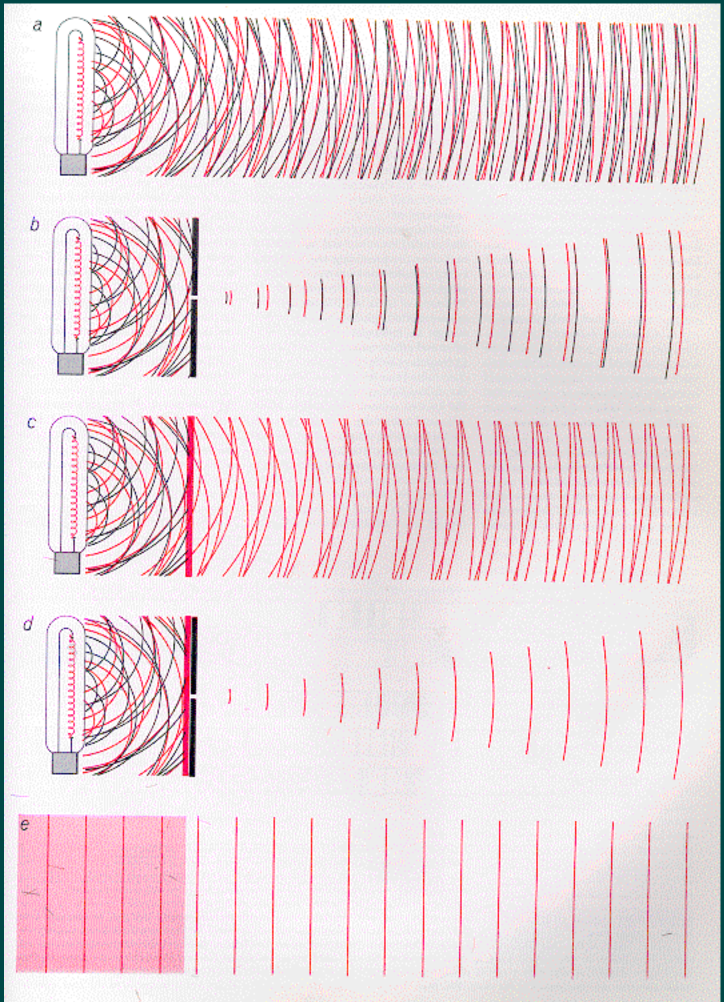
1964: First Nd:YAG laser 1.06μm (uses neodymium doped yttrium aluminium garnet crystals) by J. F. Geusic and R. G. Smith

Stimulated Emission





Coherence and Focusing



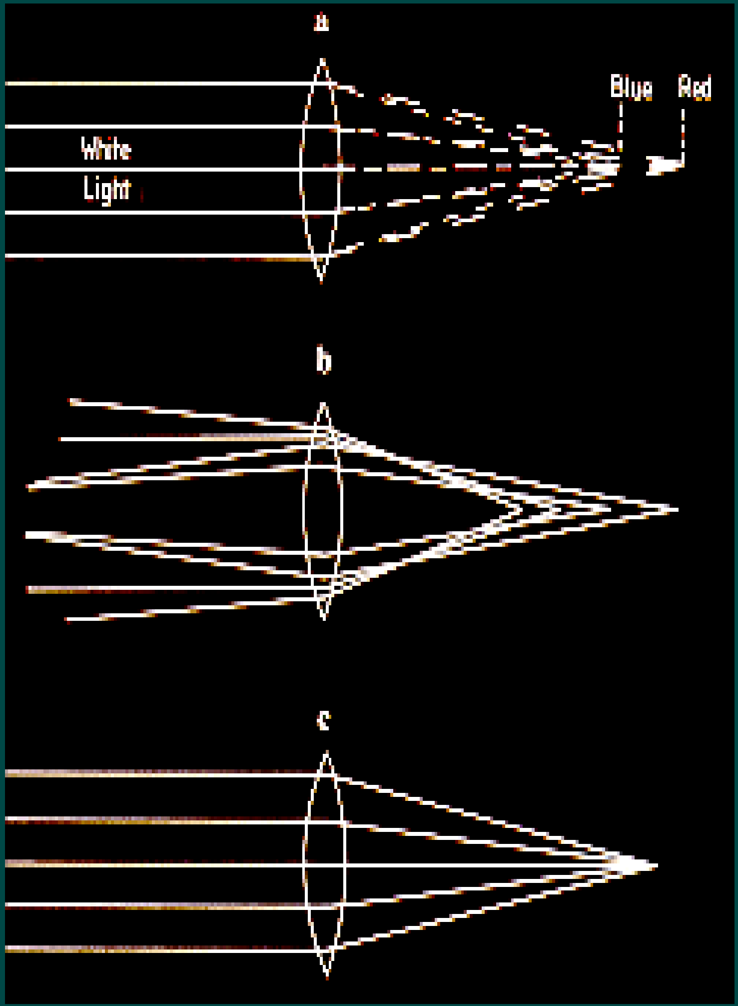
Spatially & temporally incoherent:<u>out-of-step & various wavelengths</u>

Spatially Coherent

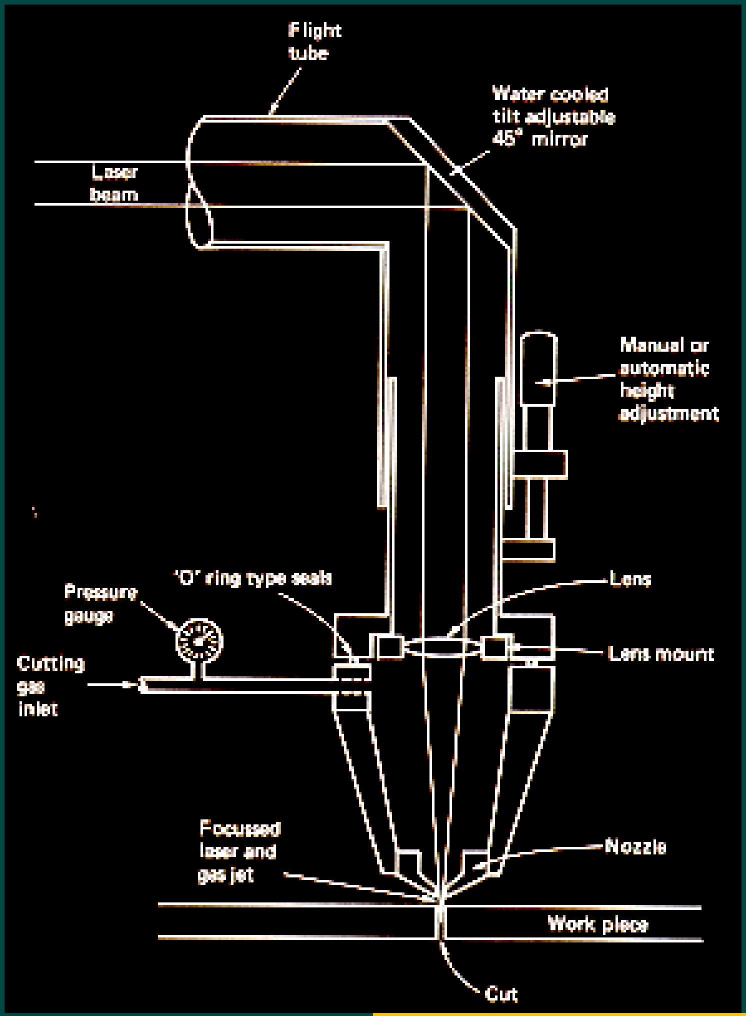
Temporally coherent single wavelength

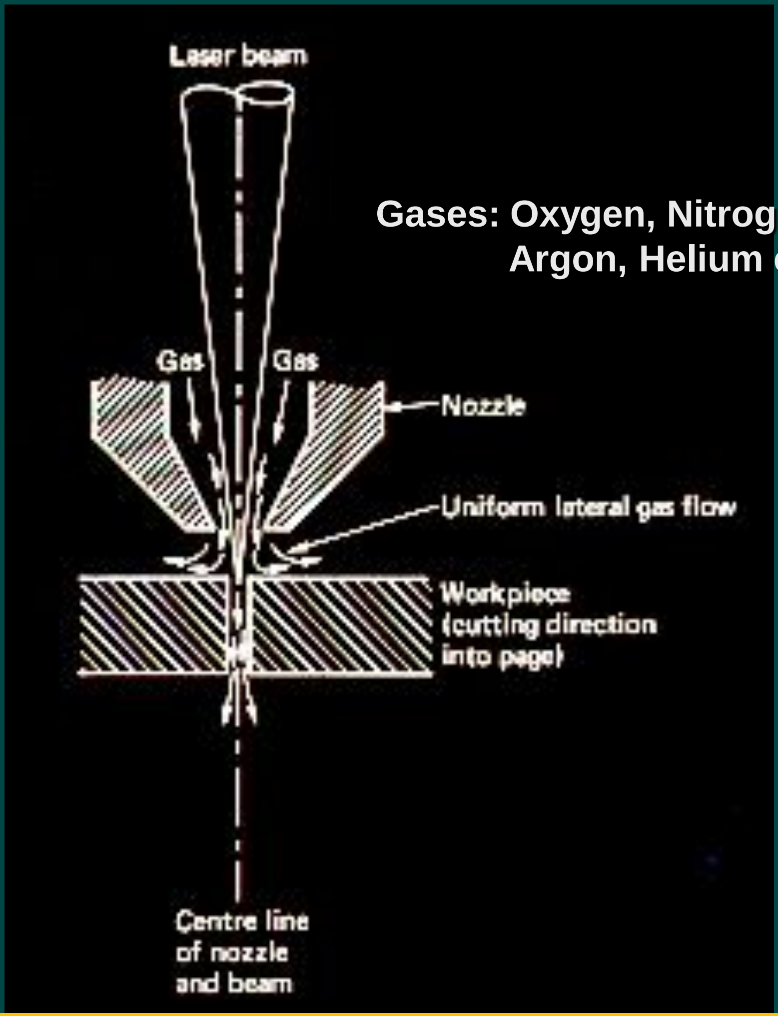
Spatially & temporally coherent- only 1% left

Laser Light
100% coherent



A Beam Focusing Lens and an Assist Gas Nozzle is required for all but UV lasers

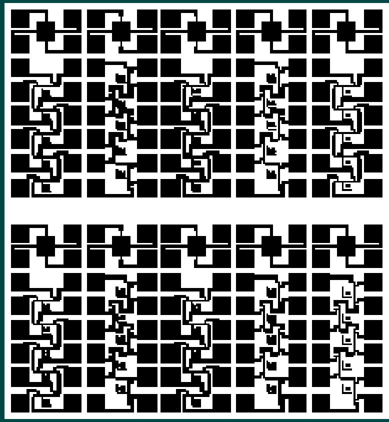


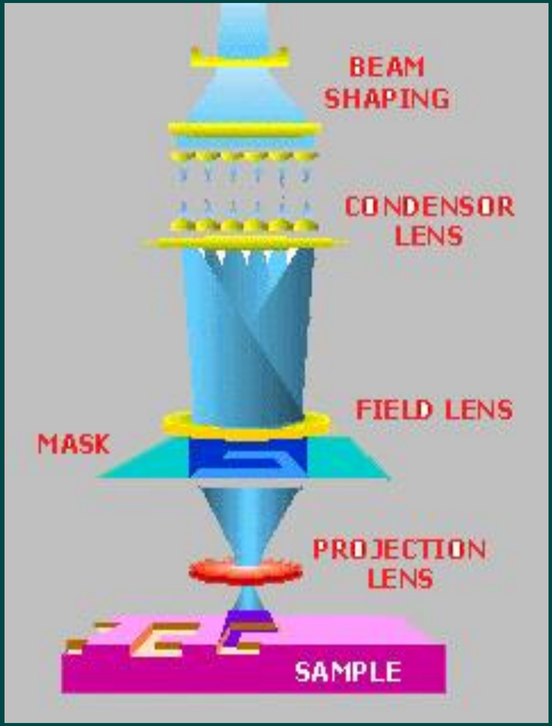


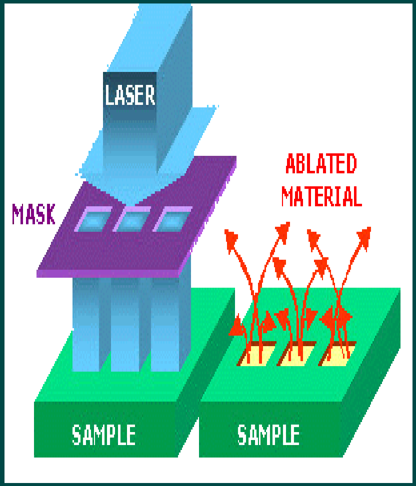
Gases: Oxygen, Nitrogen, Argon, Helium etc.

http://www.youtube.com/watch?v=uuLAkC6jrP0 laser cutting

Dry Laser Etching Ablates Material by Bond Breaking



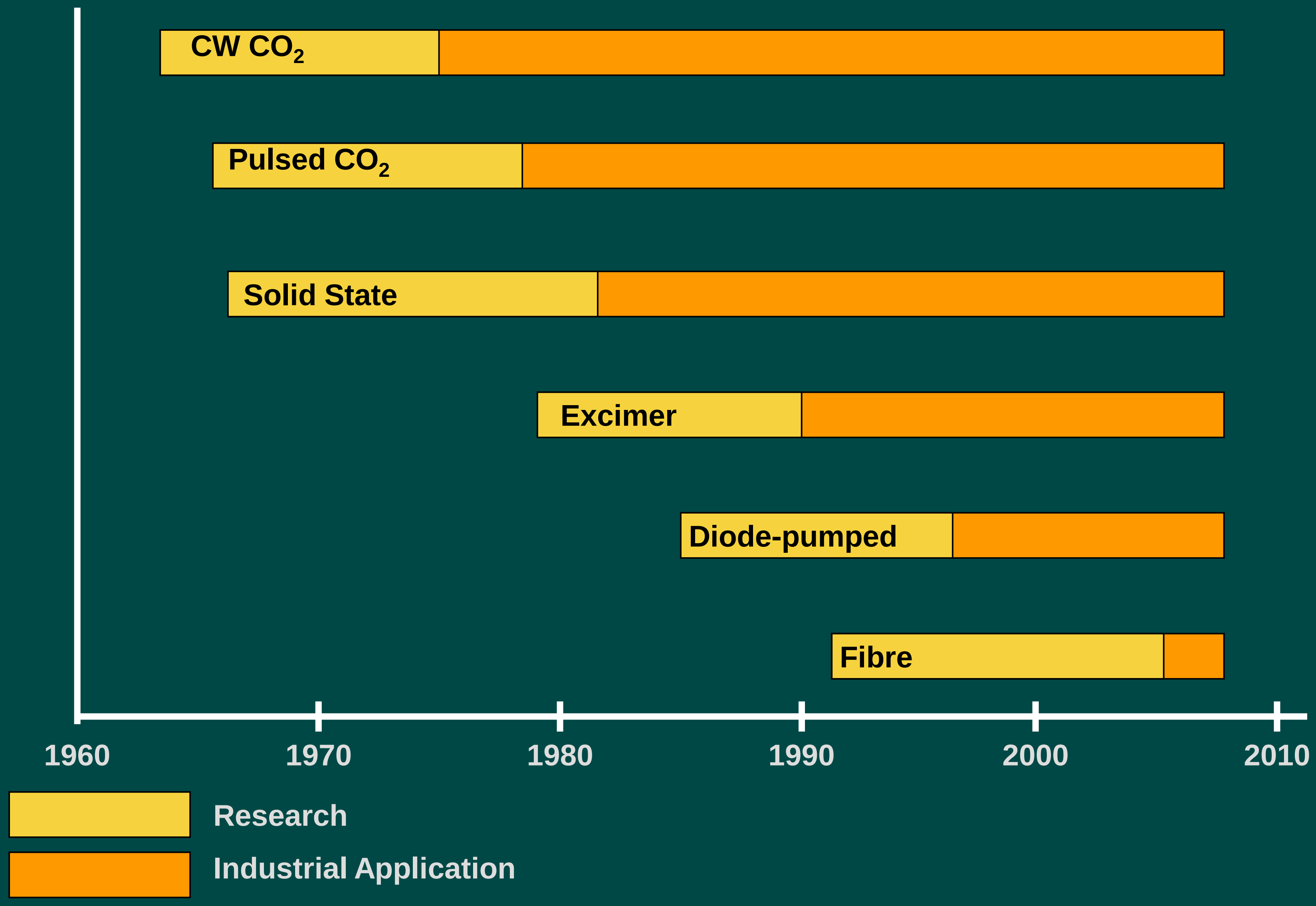




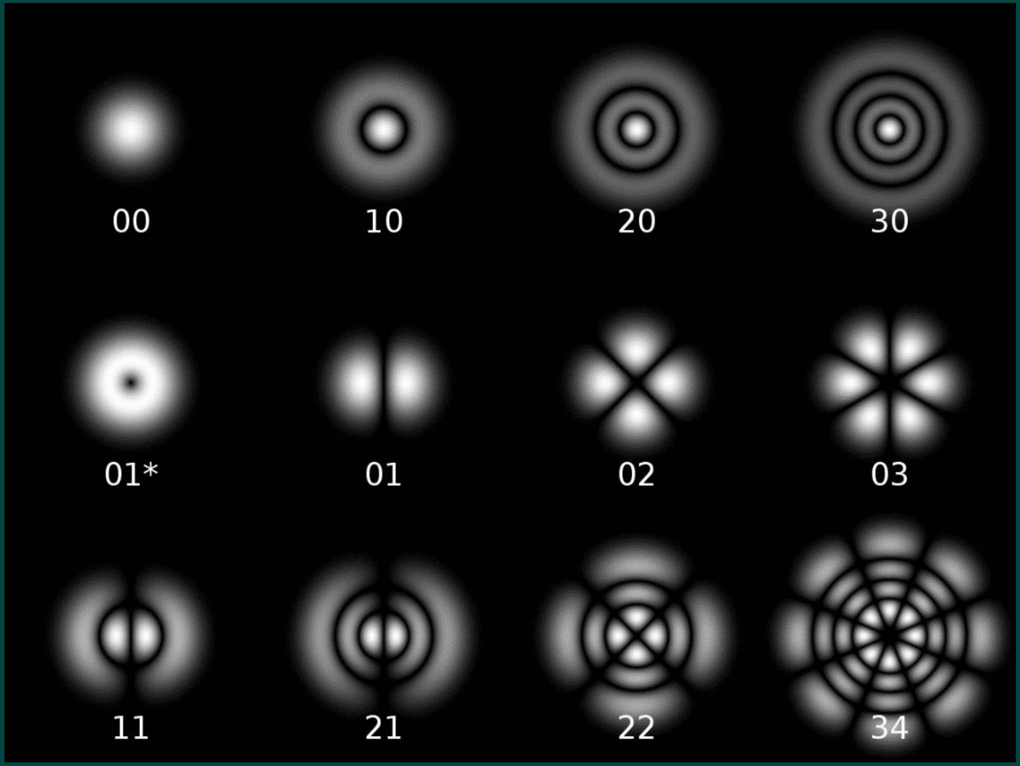
Chrome on Quartz Mask

Lambda Physik LPX 201i, 125W mean power, 2.5J/pulse,100 Hz prf, 10 to 50 ns pulse width

Evolution of Industrial Lasers



Laser Transverse Modes – cylindrical symmetry



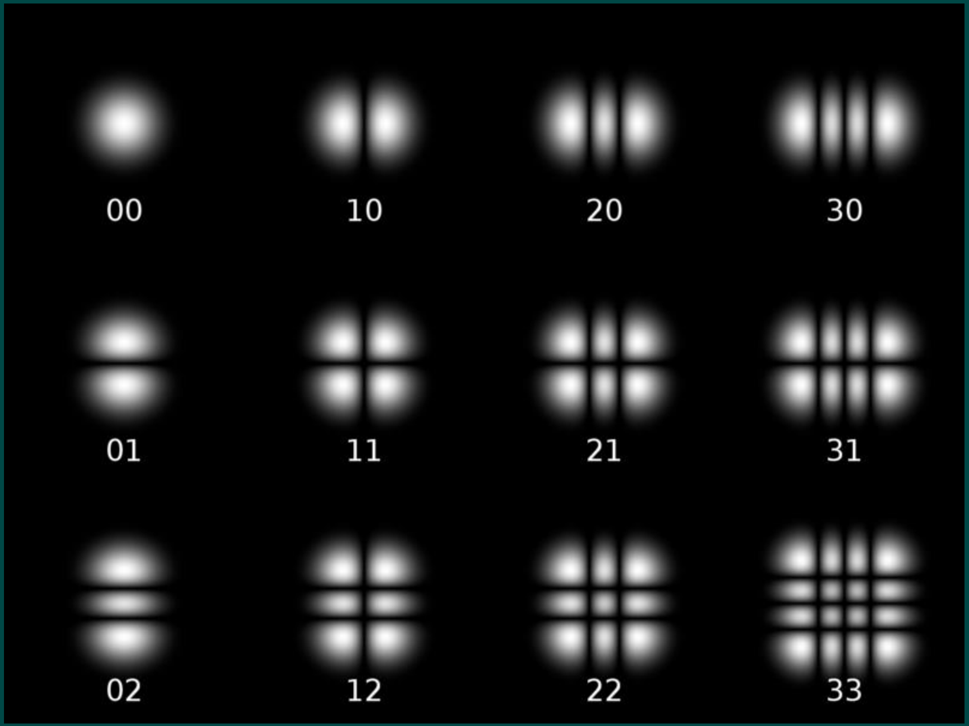
In a laser with cylindrical symmetry, the transverse mode patterns are described by a combination of a Gaussian beam profile with a Laguerre polynomial.

The modes are denoted TEM*pl* where *p* and *l* are integers labelling the radial and angular mode orders, respectively.

Laser Transverse Modes – rectangular symmetry

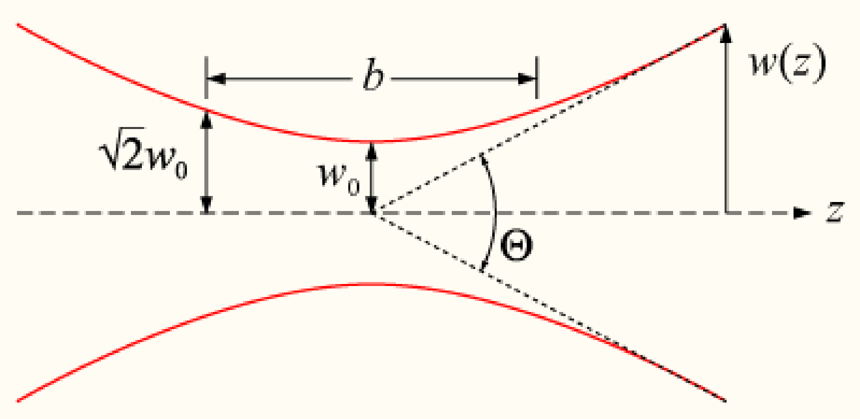
- In many lasers, the symmetry of the optical resonator is restricted by polarizing elements such as Brewster's angle windows. In these lasers, transverse modes with rectangular symmetry are formed.

- These modes are designated TEM*mn* with *m* and *n* being the horizontal and vertical orders of the pattern.



Beam waste, Rayleigh Range & Depth of Focus

For a Gaussian beam propagating in free space, the spot size w (z) will be at a minimum value w_0 at one place along the beam axis, known as the beam waist .
For a beam of wavelength λ at a distance z along the beam from the beam waist, the variation of the spot size is given by



$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2}.$$

where the origin of the z-axis is defined, without loss of generality, to coincide with the beam waist, and where

$$z_0 = \frac{\pi w_0^2}{\lambda}$$

Is called the Rayleigh range

At a distance from the waist equal to the Rayleigh range z_0, the width w of the beam is

$$w(\pm z_0) = w_0\sqrt{2}$$

The distance between these two points is called the confocal parameter or depth of focus of the beam:

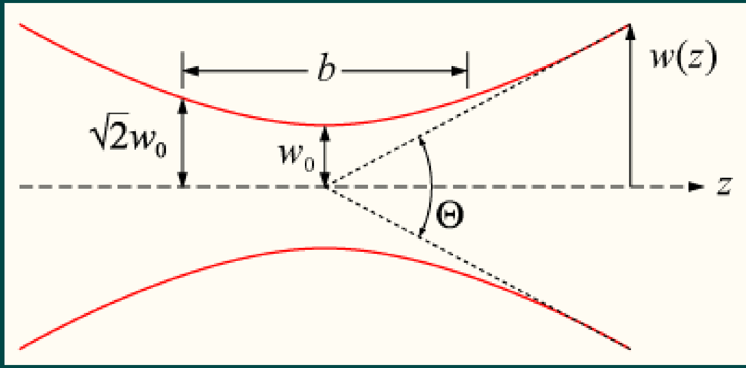
$$b = 2z_0 = \frac{2\pi w_0^2}{\lambda}.$$

Angular Spread of the Beam

The parameter w (z) approaches a straight line for $z \gg z_0$. The angle between this straight line and the central axis of the beam is called the divergence of the beam. It is given by

$$\theta \simeq \frac{\lambda}{\pi w_0} \qquad (\theta \text{ in radians.})$$

The total angular spread of the beam far from the waist is then given by $\Theta = 2\theta$



Because of this property, a Gaussian laser beam that is focused to a small spot spreads out rapidly as it propagates away from that spot. To keep a laser beam very well collimated, it must have a large diameter.

Power Output

The power P passing through a circle of radius r in the transverse plane at position z is

$$P(r,z) = P_0\left[1 - e^{-2r^2/w^2(z)}\right],$$

Where:

$$P_0 = \frac{1}{2}\pi I_0 w_0^2$$

$\omega_0 = M^2 \lambda / \pi \Theta$

is the total power transmitted by the beam

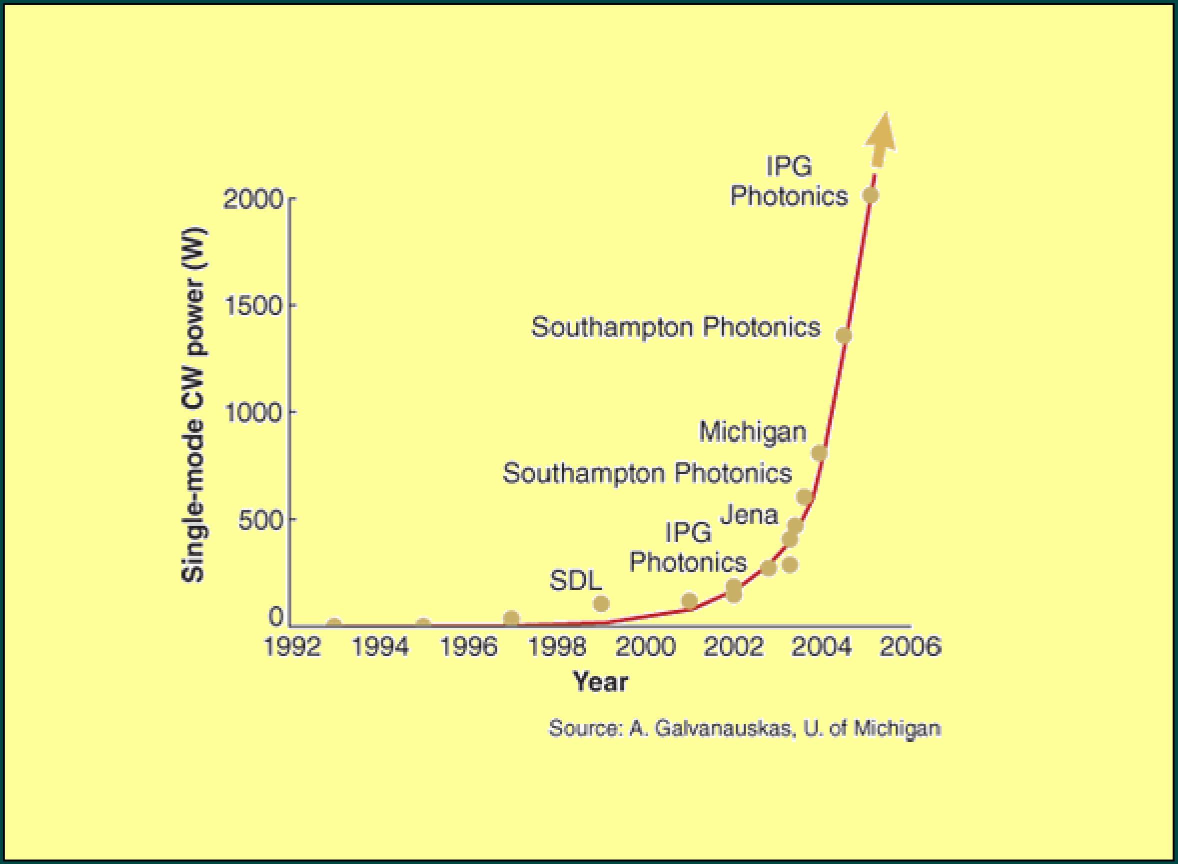
M^2 Factor – Beam Quality Factor

- The M^2 factor, also called *beam quality factor* or *beam propagation factor*, is a common measure for the beam quality of a laser beam. According to ISO 11146, it is defined as the beam parameter product divided by λ/π, the latter being the beam parameter product for a diffraction-limited Gaussian beam with the same wavelength. In other words, the beam divergence is
- $\theta = M^2 \lambda/\pi\omega_0$
- where w_0 is the beam radius at the beam waist and λ the wavelength. A laser beam is often said to be "M^2 times diffraction-limited". A diffraction-limited beam has an M^2 of 1, and is a Gaussian beam. Smaller values of M^2 are physically not possible. A Hermite-Gaussian beam, related to a TEMnm resonator mode (→ higher-order modes), has an M^2 factor of $(2n + 1)$ in x direction, and $(2m + 1)$ in y direction.

M^2 Factor – Beam Quality Factor

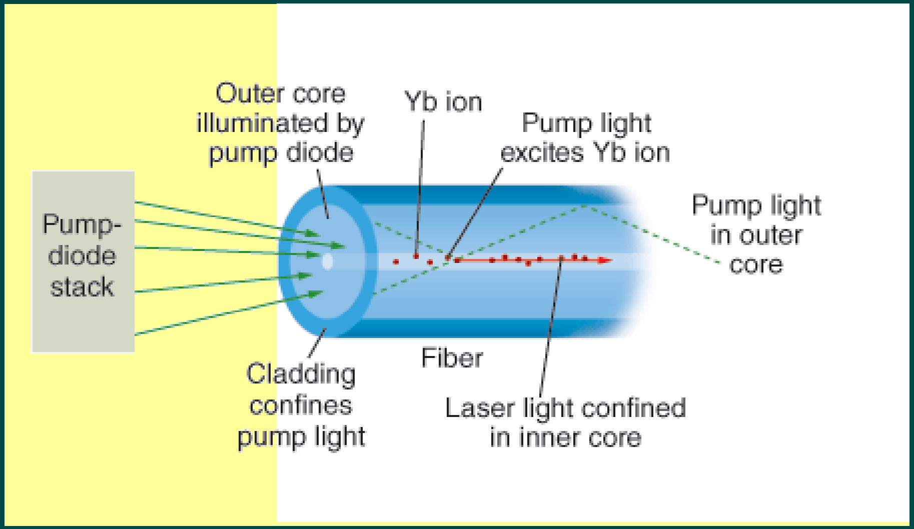
- The beam waist of a laser beam is the location along the propagation direction where the beam radius has a minimum. The *waist radius* is the beam radius at this location.
- The M^2 factor of a laser beam limits the degree to which the beam can be focused for a given beam divergence angle, which is often limited by the numerical aperture of the focusing lens.
- Together with the optical power, the beam quality factor determines the brightness (more precisely, the radiance) of a laser beam.

High Power Fibre Lasers



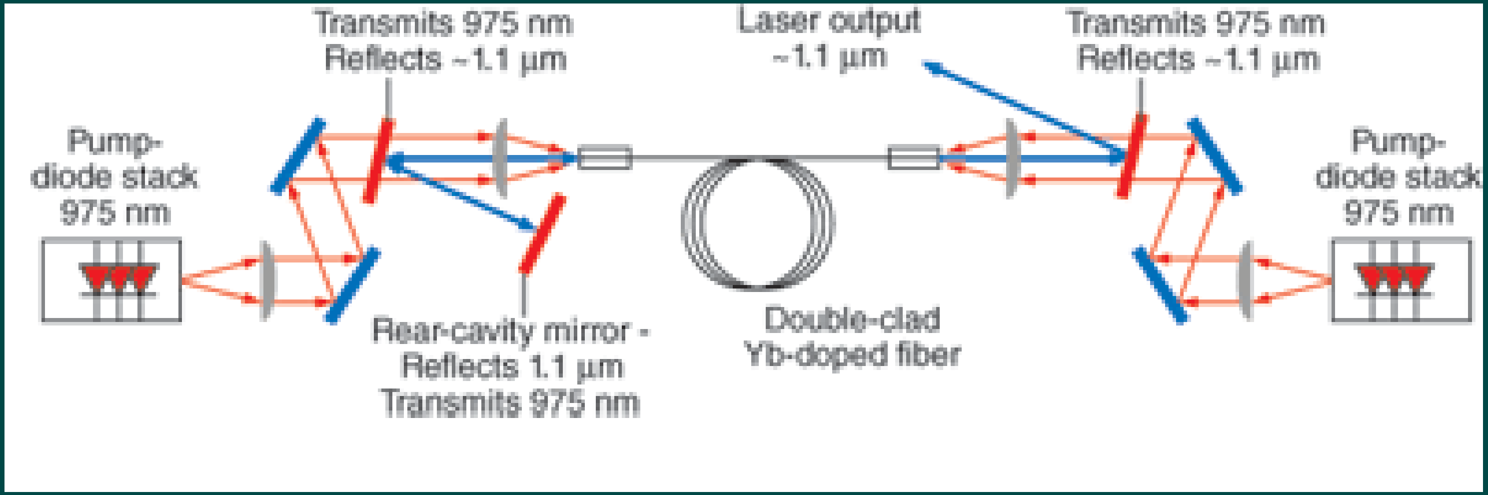
The steady march of high-power single-mode output from ytterbium-doped fiber lasers is continuing.

Fibre Laser Operation



Pump light from a diode-laser stack illuminates the outer core of a dual-core fiber (focusing optics are not shown for simplicity).
The cladding confines the pump light in the outer core so it passes through the inner core. One pump photon excites an ytterbium atom in the inner core, which emits light that is confined in the inner core,
becoming part of the fiber-laser beam

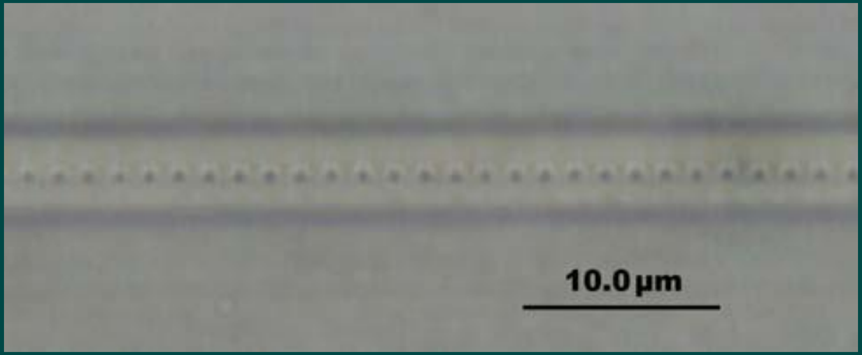
Optical Arrangement



A high-power Yb-doped fiber laser is pumped from both ends. Filters transmit the 975-nm pump light into the laser cavity while serving as mirrors that reflect the 1.1-µm laser light. This is a simplified version of the arrangement that generated 1.3 kW CW in experiments at Southampton.

Fibre lasers are available up to 50 kW in power

http://www.youtube.com/watch?v=LVpD5y7ngA4



Optical microscope image of the core of a Ytterbium doped fibrelaser showing the individually inscribed grating periods of a grating for operation at 1064 nm.

Courtesy: Graham D. Marshall et al

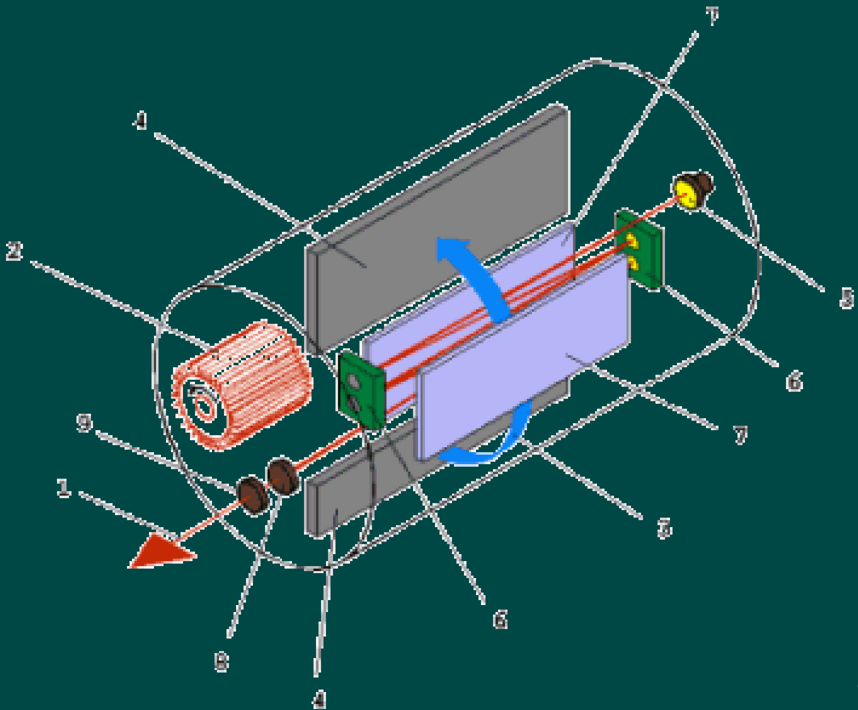
High Power Materials Processing Lasers

- Carbon Dioxide - up to 100kW more usually 2 to 7kW - 10.6μm
- Carbon Monoxide - not generally available, up to 5kW - 5 to 6μm
- Nd-YAG - up to 4.5kW - 1.06μm
- UV - Argon Ion 2W, HeCd, Tripled YAG 5W
- Diode Lasers 2 kW
- Fibre Lasers 2kW single mode 50kW multimode >25% efficiency

High Power Micro-machining Lasers

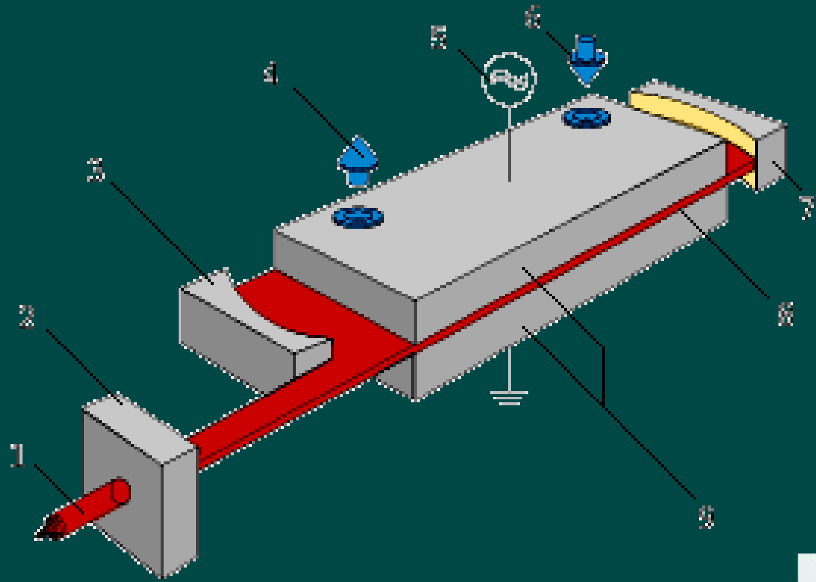
- Copper Vapour Lasers 511& 578 nm, 20-30 ns pulses, 2-20kHz, 50 to 500 kW peak power
- Excimer - pulsed mean power 1kW – UV – 157nm, 193nm, 248nm,308nm, 351nm, 1000Hz, 1kW
- Nd-YVO_4 – 355nm Neodymium Vanadate 38ns pulses, 10kHz, 6 W mean
- Ti:Sapphire – 850nm , 250kHz, 100 fs pulses, 300kW,

8kW CO_2 Laser



1. Laserbeam
2. Tangential blower
3. Gas flow direction
4. Heat exchanger
5. Rear mirror with real time power monitor
6. Fold mirror
7. HF-electrodes
8. Output mirror
9. Output window

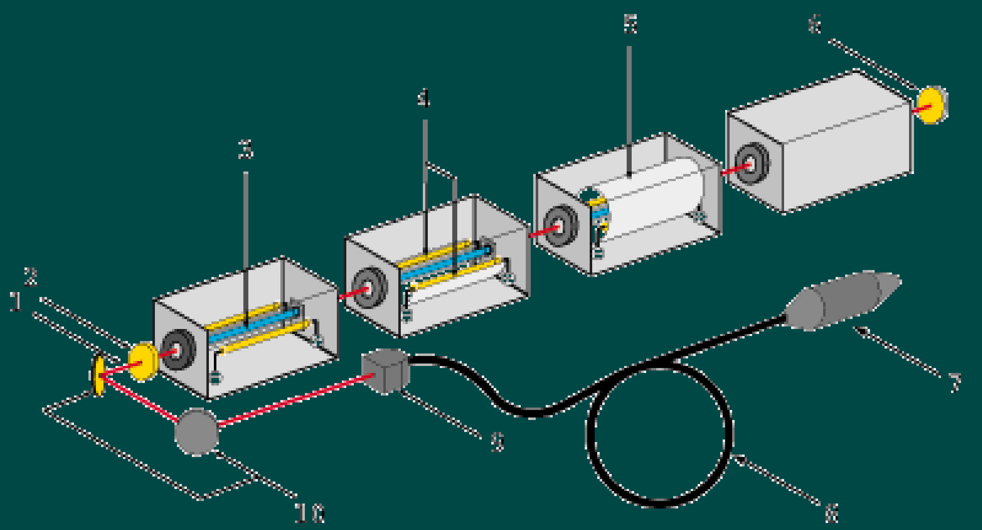
3.5kW Diffusion Cooled CO_2 Laser - CW or 5kHz pulsed



1. Laserbeam
2. Beam shaping unit
3. Output mirror
4. Cooling water
5. RF excitation
6. Cooling water
7. Rear mirror
8. RF excited discharge
9. Waveguiding electrodes

Courtesy of Rofin

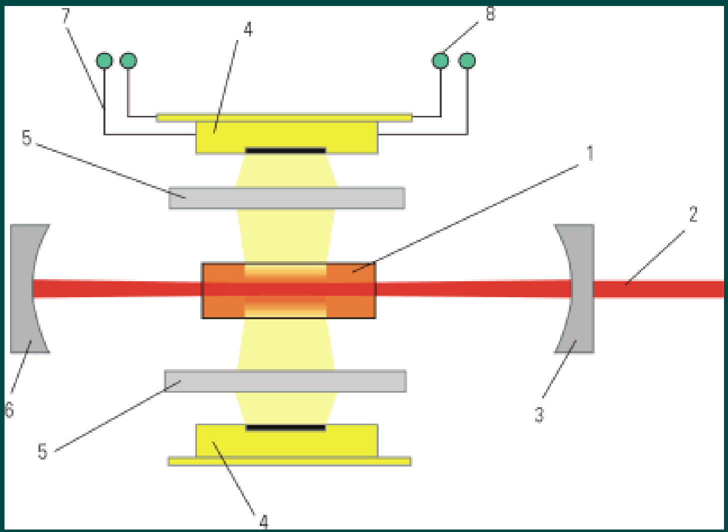
Flash Lamp Pumped 2.7kW cw or Pulsed (500 Hz) Nd-YAG Laser



1. Laser beam
2. Output mirror
3. Nd:YAG rod
4. Excitation lamps
5. Reflector
6. Rear mirror
7. Focusing unit
8. Fibre - 600 microns
9. In-coupling unit
10. Beam bending mirrors

Courtesy of Rofin

4.4 kW cw Diode Pumped Nd-YAG Laser



1. Nd:YAG rod
2. Laserbeam
3. Output coupler
4. Diode arrays
5. Collimating optic
6. High-refelectance mirror
7. Cooling
8. Electrical supply

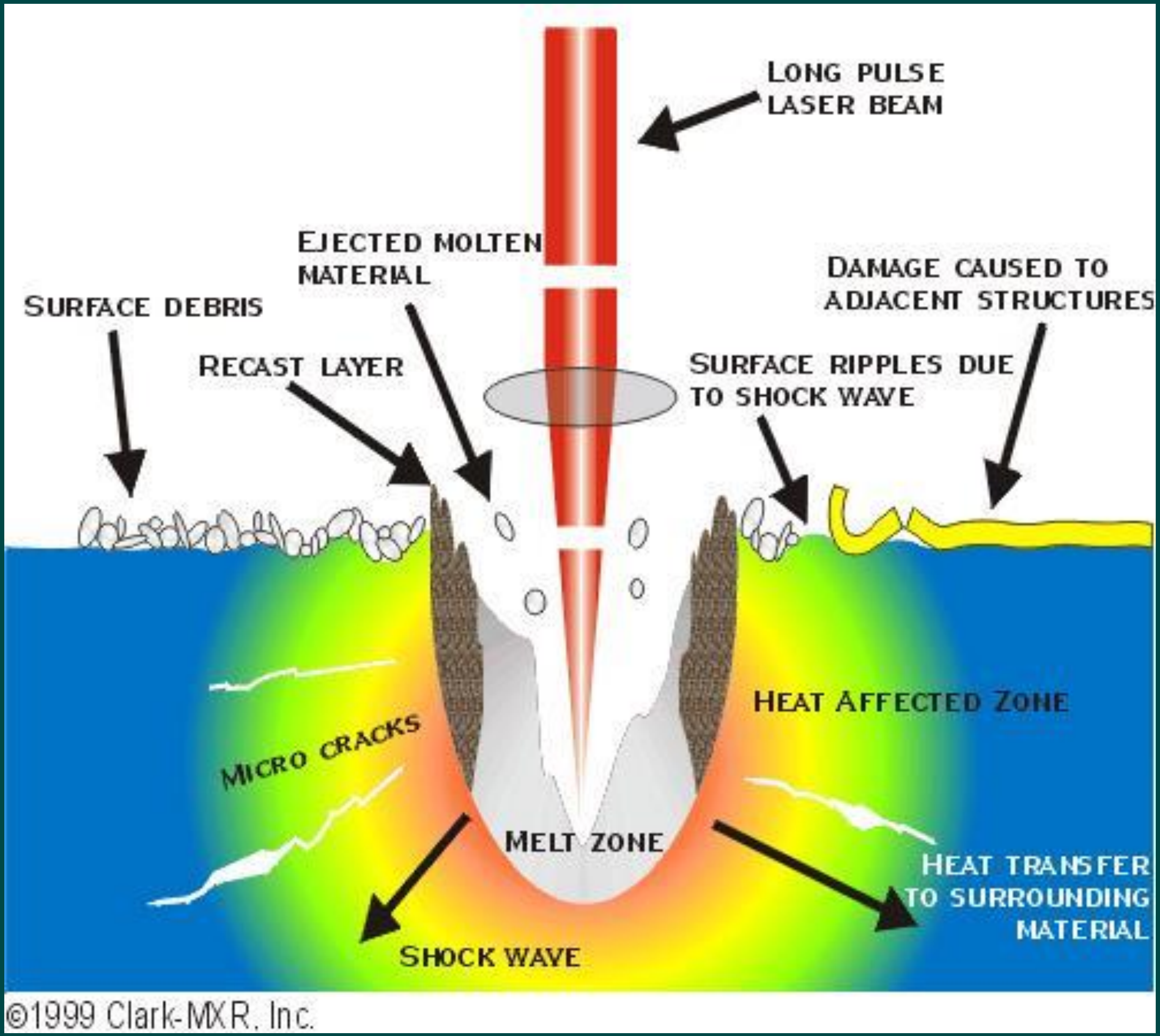
9. 300 micron fibre

Courtesy of Rofin

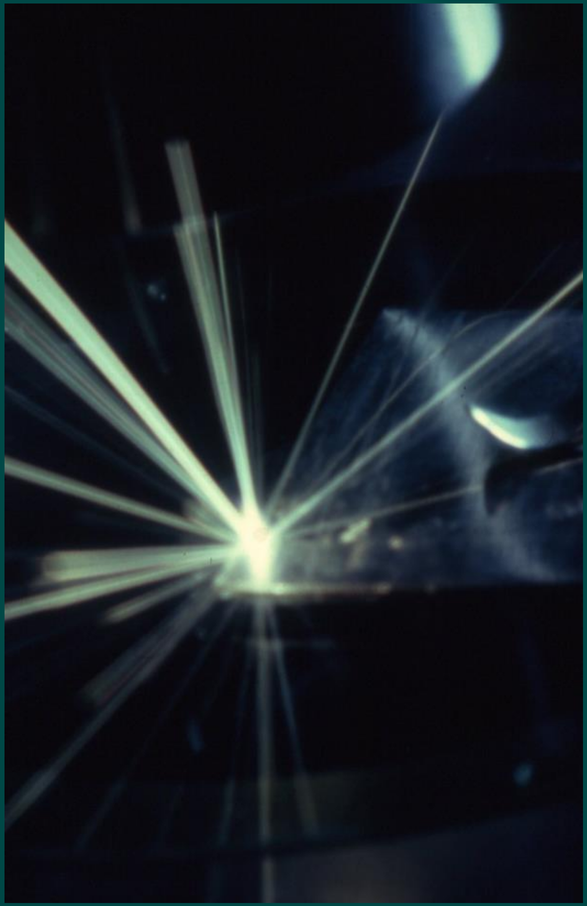
Industrial Application Areas

- Electronics
- Semiconductor
- Aerospace
- Automotive
- Medical Device
- Metrology
- Package Coding
- General Manufacturing

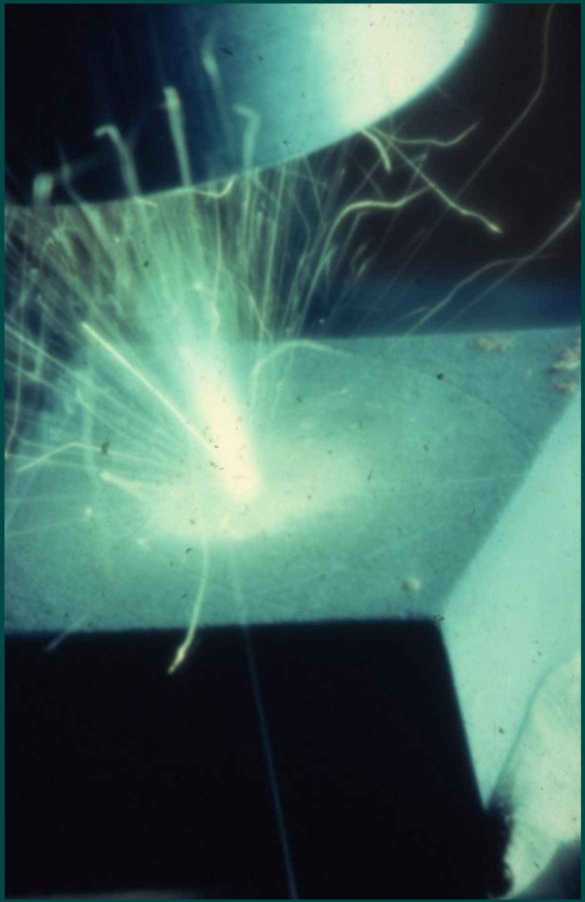
Long Pulse Interaction



Nd: Glass Laser Interactions

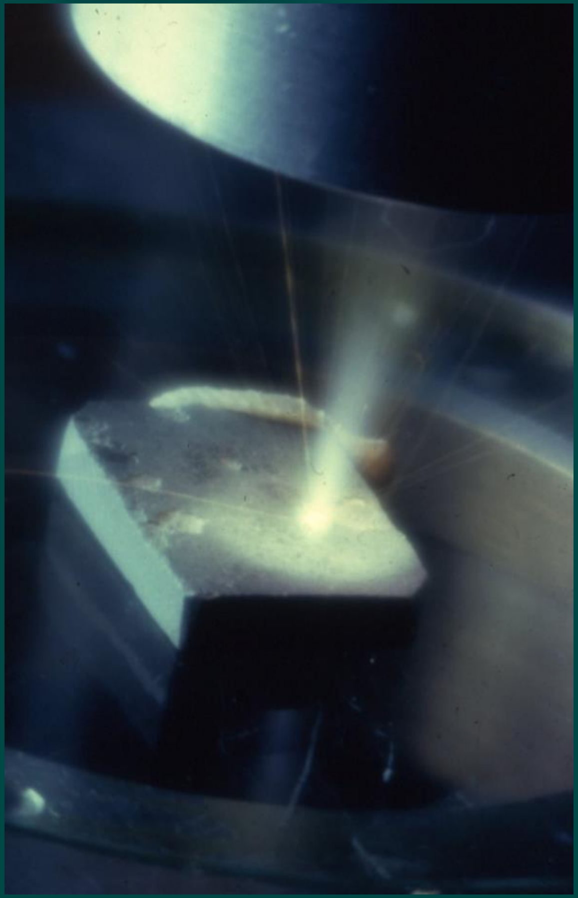


Titanium

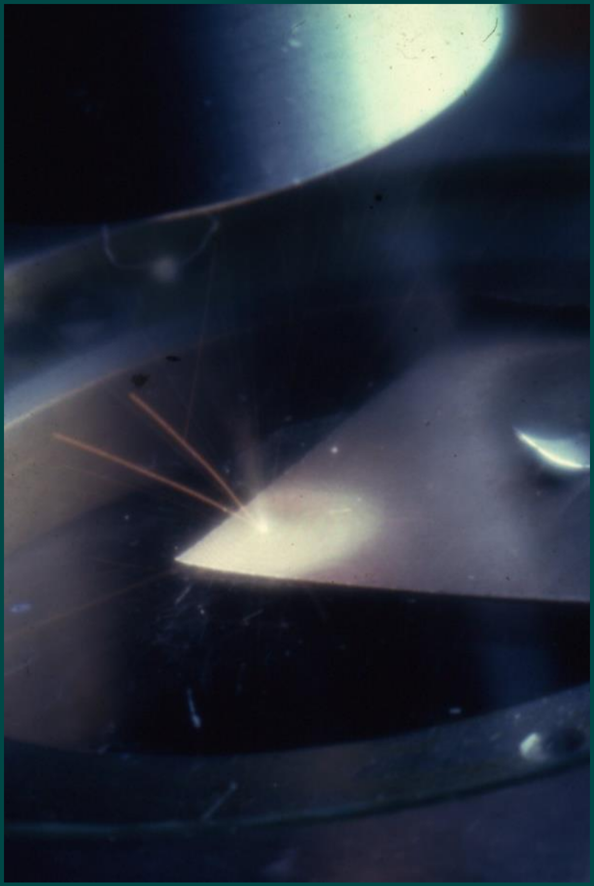


Zirconia Dioxide

Nd: Glass Laser Interactions

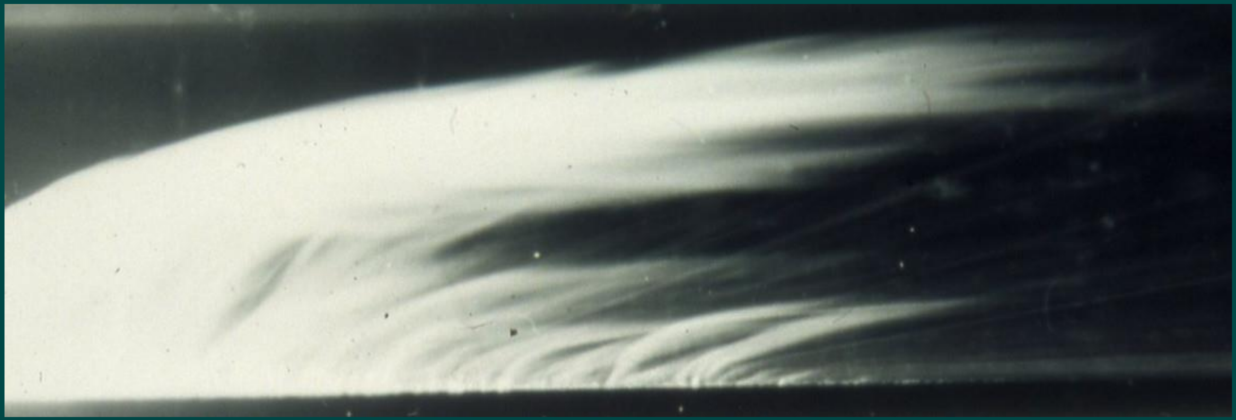


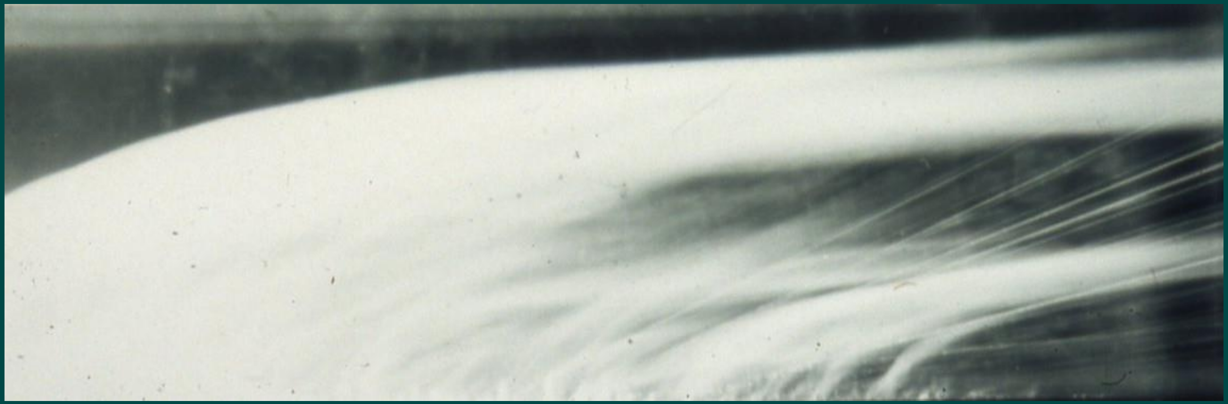
Silicon Nitride



Tantalum

Streak Photographs of Laser Drilling with an Nd:Glass Laser





Computer Numerically Controlled (CNC) Beam delivery Systems

http://www.youtube.com/watch?v=3Geukorbw58

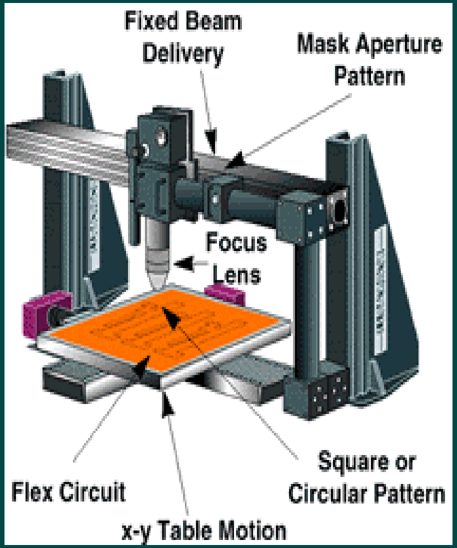
http://www.youtube.com/watch?v=pjUa3x31DK8&feature=endscreen&NR=1

Laserdyne 550 Beam Director

Multiaxis: cutting, drilling, welding for manufacturers in aerospace, automotive and job shop industries

Laserdyne 890 Beam Director

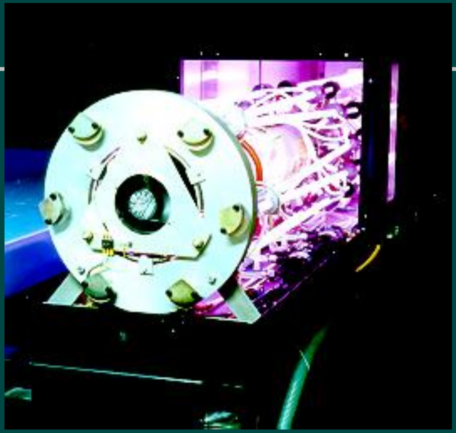
Multiaxis: cutting, drilling, welding for manufacturers in aerospace, automotive and job shop industries



Small Batch Rapid Manufacture using Lasers

AF8P - 8kW Carbon Dioxide Laser can run CW or Pulsed up to 3.3kHz

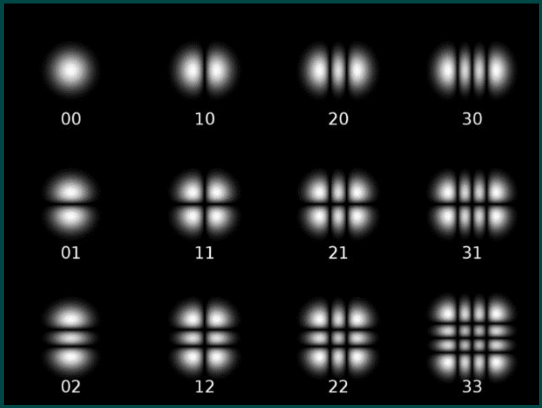
MFK 1 kW CO_2 Laser



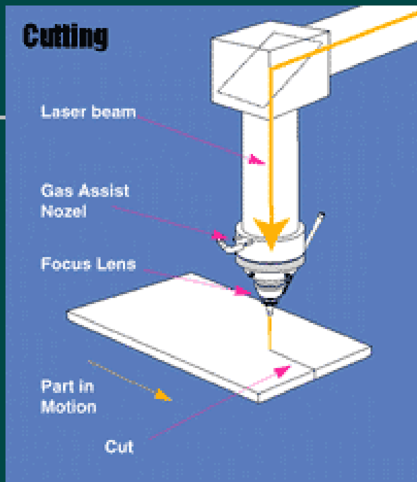
AF8P- CO: 1 - 2.5kW Carbon Monoxide Laser can run CW or Pulsed up to 3.3kHz

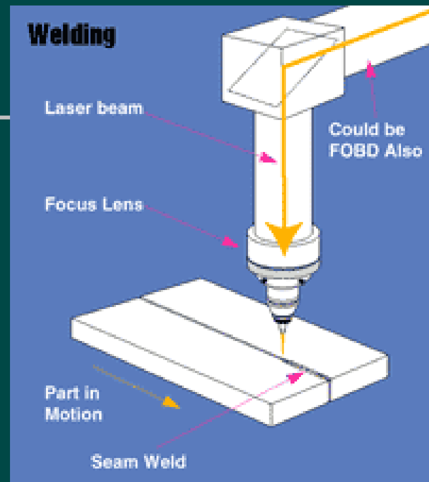
Weld Penetration in 12 mm SS

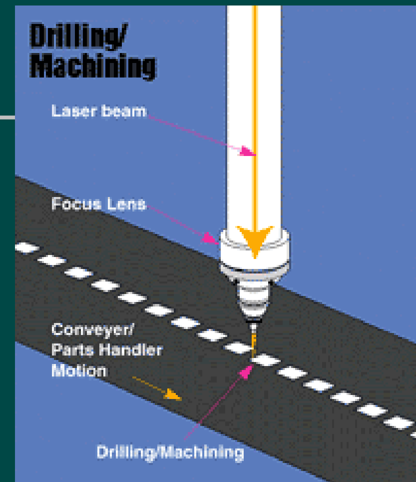
Case Hardening of a Camshaft

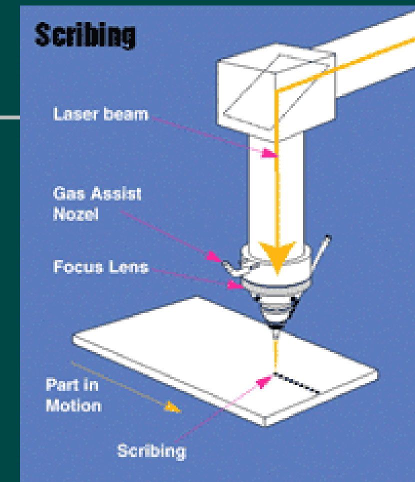


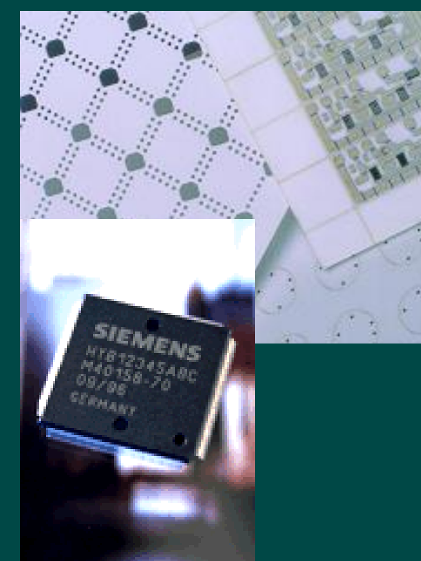
Rapid Programmable Manufacture Using Lasers



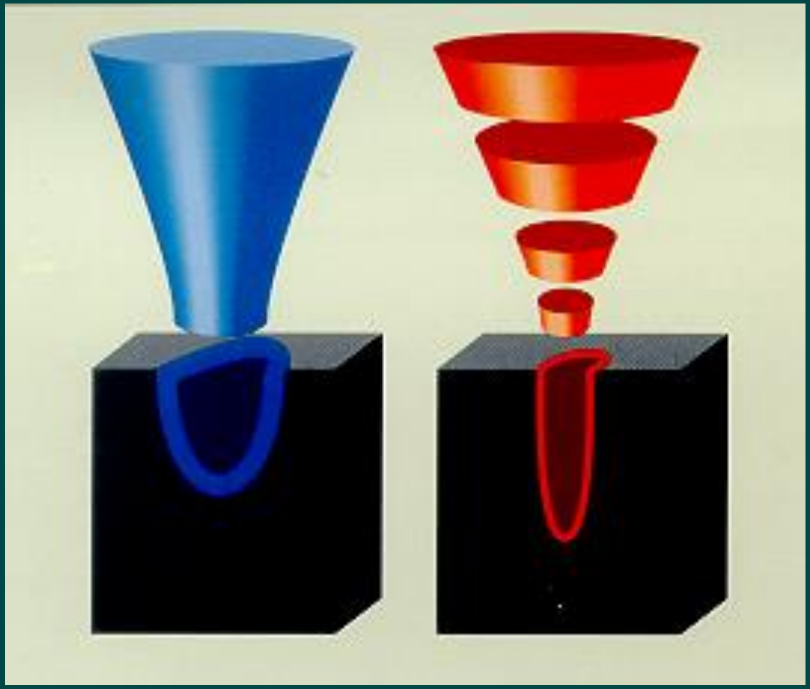






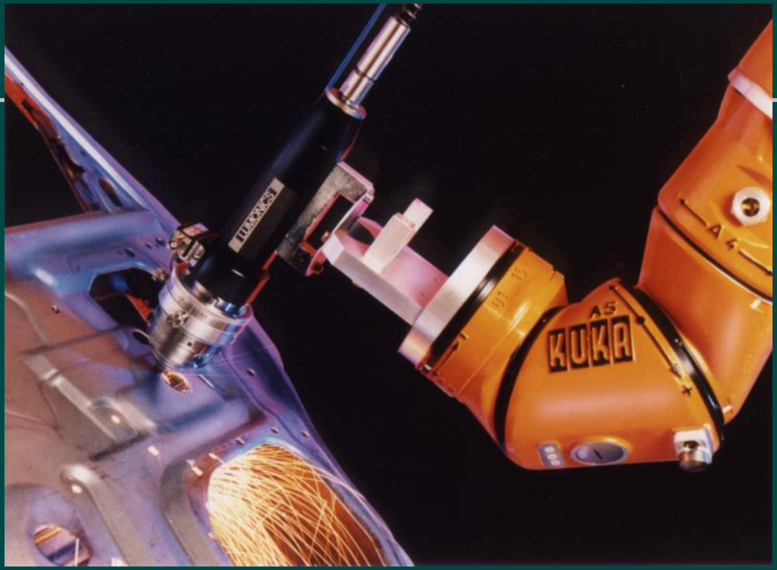


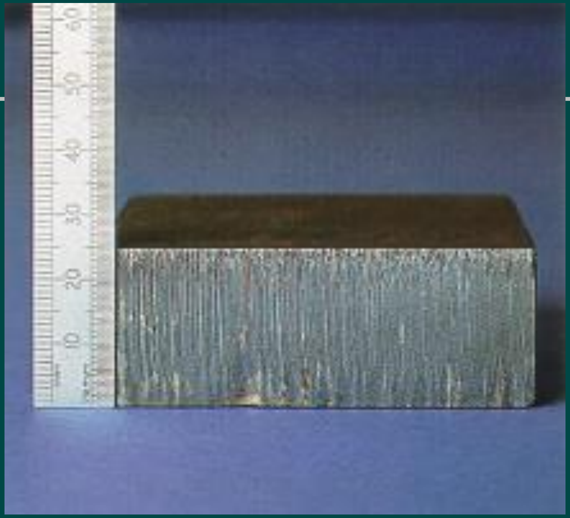
Pulsing CW Lasers



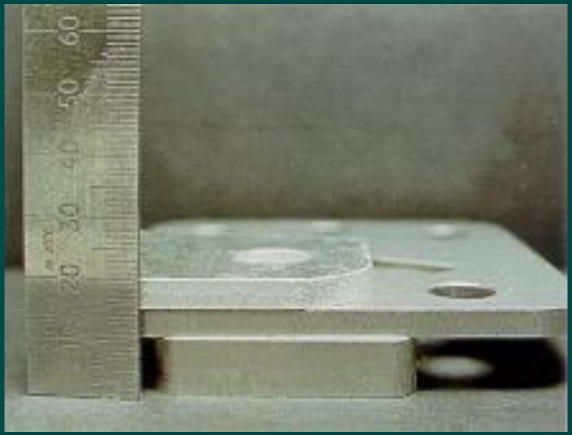
- Pulsed lasers give a sharper, hotter knife
- Narrower focus
- It gives greater process control
- High instantaneous power allows processing of highly reflective metals like aluminium

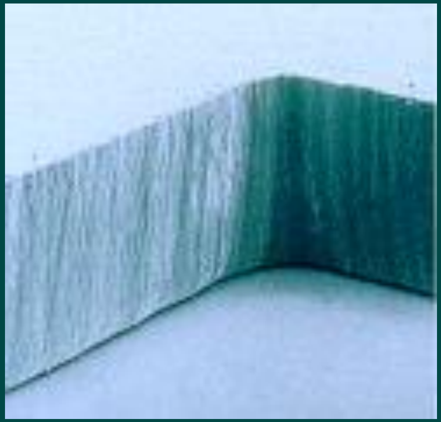
Laser Cutting





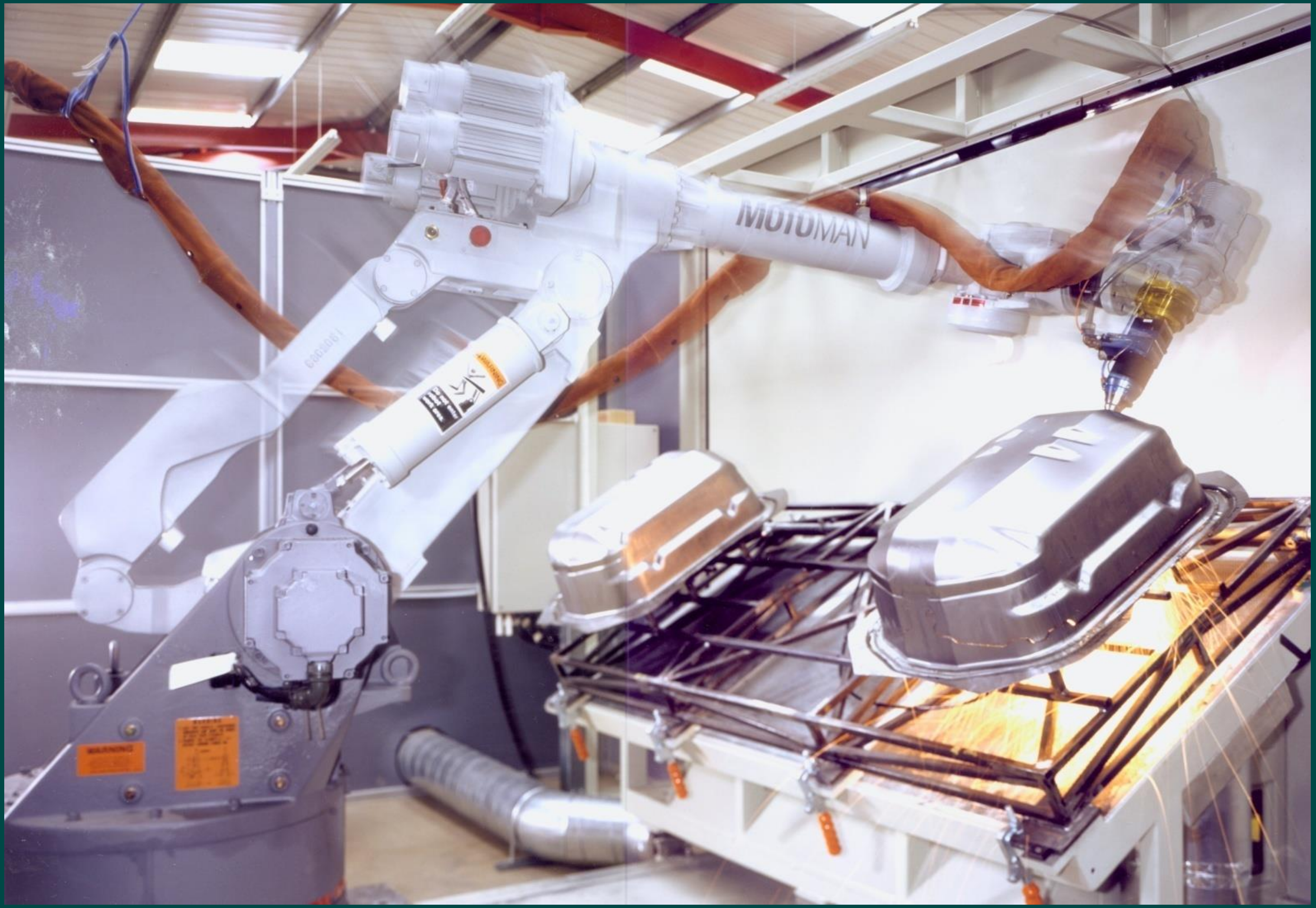
25mm Armour Plate





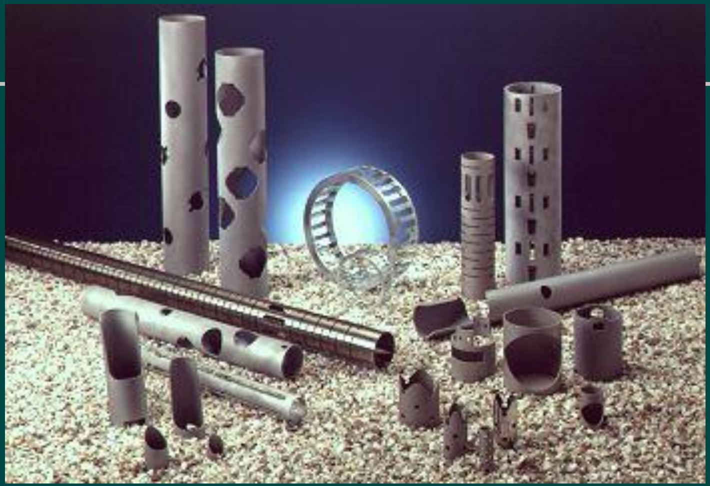
Inert gas (N_2) cut samples of 10 mm stainless, 5 mm stainless, 6 mm aluminium

YAG laser trimming of pressings

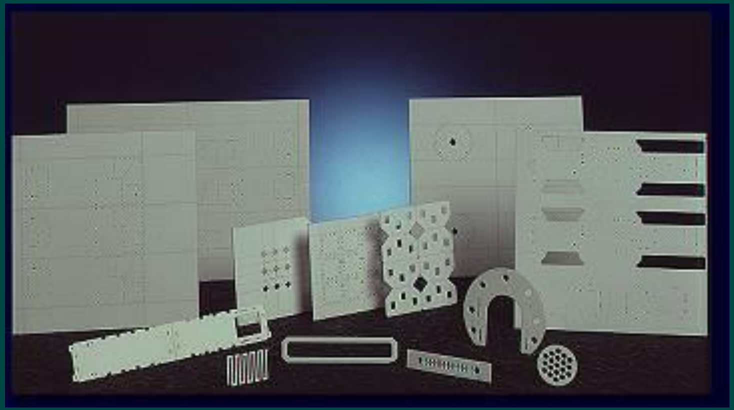


Laser Cutting Nd-YAG & CO_2

Laser cutting of sheet metal is now widely accepted, up to 20 mm thick



Laser cutting of tubes



Laser cutting and scribing of ceramics, eg. alumina

http://www.youtube.com/watch?v=UeGVbtrrHjE&feature=related tube cutting

Laser Cutting

http://www.youtube.com/watch?v=be4LrGn0lPg cut and bend

- In principle, both CO_2 and Nd:YAG lasers are suitable for this application.
- The decision for one or the other beam source is influenced by such factors as the geometry of the cut, the cycle time, the system technology and above all the material.
- Cutting in two dimensions, which is the most common case, is the domain of the CO_2 laser, because it yields the best cost-benefit ratio.
- Typical cutting speeds in steel are, for example, in the region of approx. 8 meters per minute for 1 mm, 4.5 meters per minute for 3mm and 1.5 meters per minute for 8 mm thick material.
- High reflectivity materials such as: Gold, Silver, Copper, Aluminium and Brass are possible with CO_2 but better with Nd-YAG

Cutting Glass with CO_2 Lasers

http://www.youtube.com/watch?v=KOHvJMExCN0

When cutting quartz glass, the advantages of the laser over traditional cutting processes lie in the absence of wear on the beam, which works contact-free. Furthermore, the laser technique creates a significantly improved quality of cut compared with other processes. It causes no microscopic cracks, and thus permits the narrowest of webs. The typical cutting speed varies between 0.2 and 1.5 meters per minute, depending on the thickness of the material, when CO2 lasers are used. Other types of laser cannot be used, because glass does not absorb the beam.

http://www.youtube.com/watch?v=Wzz7k-bP7MQ&feature=related

Cutting Thermoplastics with CO_2 Lasers

http://www.youtube.com/watch?v=7Jf8kk3Lq74

Thermoplastics can be cut by comparatively low-power CO_2 lasers in the range of 100 to 300 Watts. Depending on the setup of the application, separation cuts or polishing cuts (visually clean cut edge) can be carried out. One important area in which laser-cut parts of this kind are used is in illuminated advertising, in which plastic sheet is often glued to the material before or after cutting. The cutting speeds depend to a great extent on the desired quality of the edges, but an example would be 2.5 meters per minute for separation cutting in 4 mm material at 200 Watts.

http://www.youtube.com/watch?v=I_FmlorBGqg&feature=related

Nd-YAG Laser Drilling of Refractory metals

Jet-engine turbine blade
- Nimonic alloy

0.5 mm holes at 20 degrees to the surface
in a jet engine combustion chamber

http://www.youtube.com/watch?v=83OQTZZ4ML8

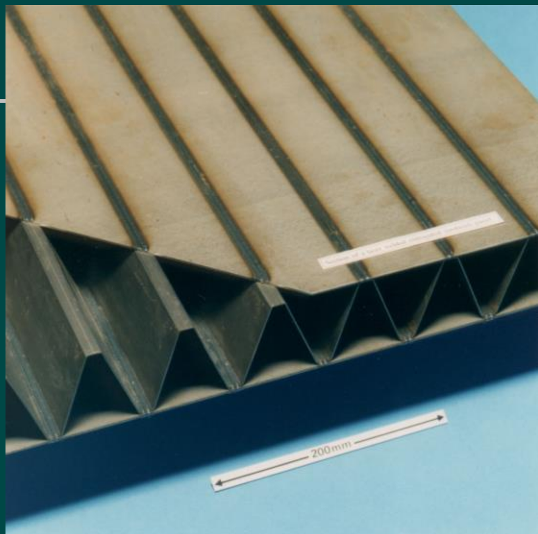
Nd-YAG Laser Welding

Car Body Welding

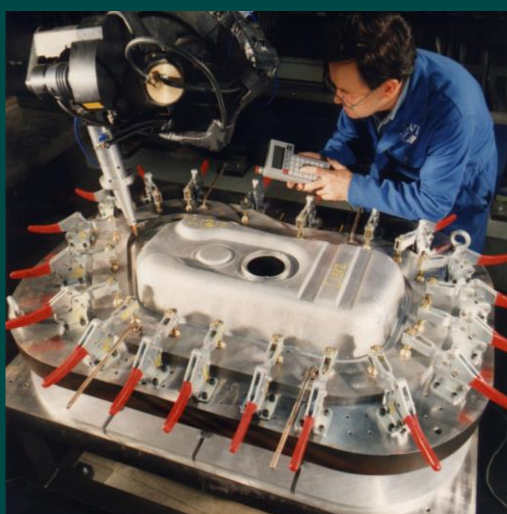
Laser Welded Tailored Blank

Laser Welded Car Door

Laser Welding



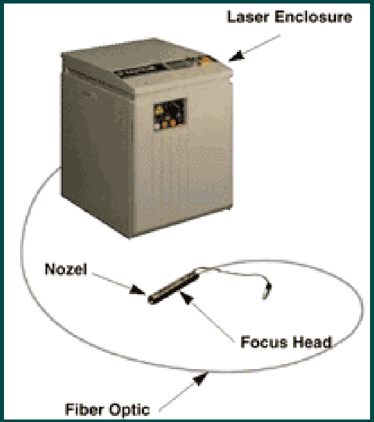
Light weight sandwich panel



5 axis CO_2 laser welding of a petrol tank

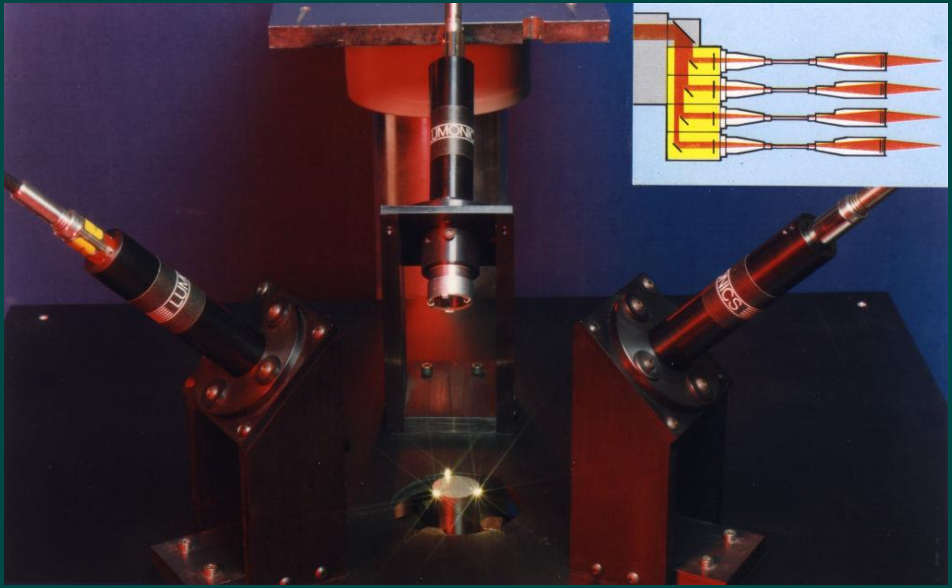
Arc assisted laser welding

Nd-Yag Laser Welding has the edge over CO_2



Airbag detonator hermetically welded

Fuel Injector Elements



Hermetically welded pacemaker

Nd-Yag Laser Welding

Seam welding of relay cans. The
The low heat input prevents damage
to the adjacent glass to metal seals.

Ball bearing cage. A two fibre
system heats both sides of the
weld simultaneously

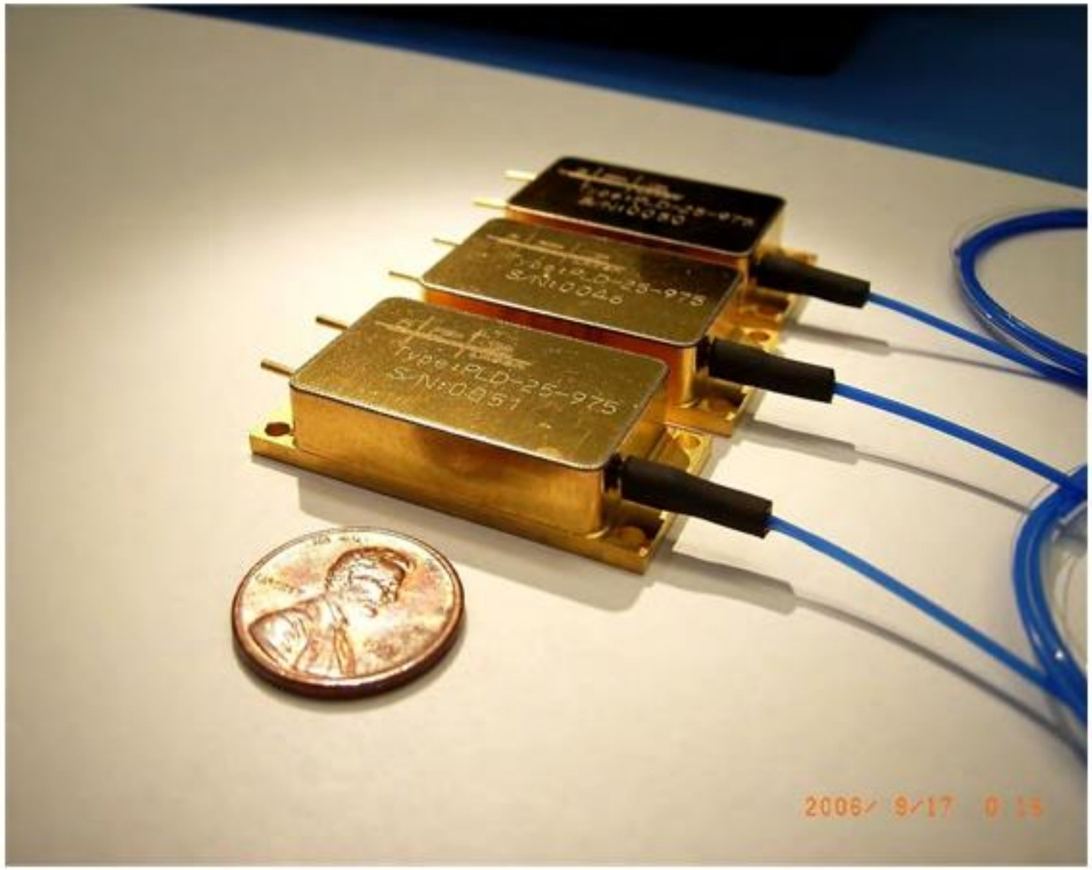
Shadow mask of TV tube welded
to its support structure.
Alignment is maintained to 5µm

This diaphragm is only 0.04 mm
thick. The component is welded
at 15 mm/s without buckling

Welding silicon iron motor laminations
eases handling prior to winding.

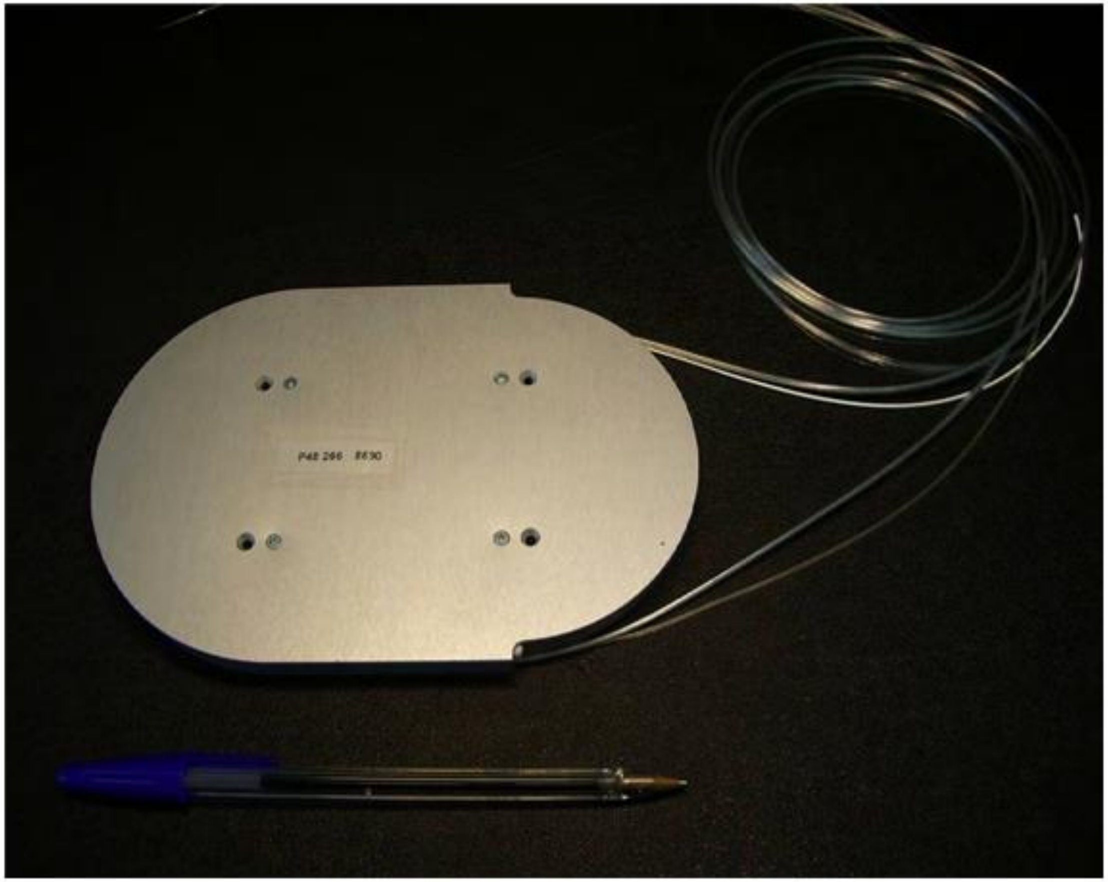
Welding of battery
terminals

25W Pump Diode Modules - IPG

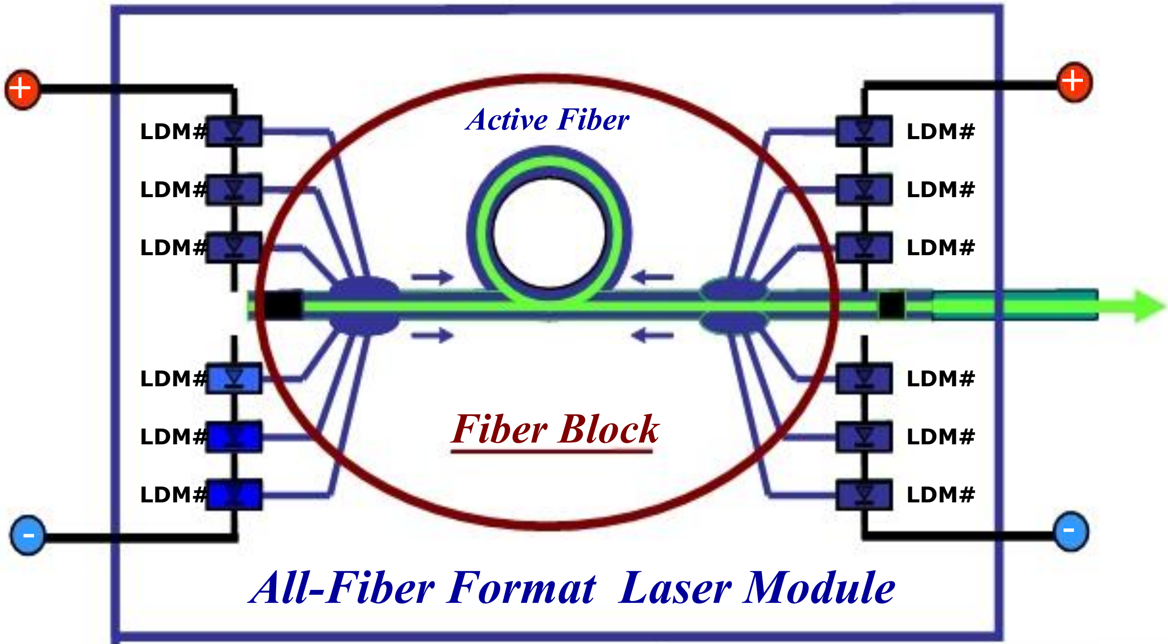


https://www.youtube.com/watch?v=ofEqFlqkiS0 fibre laser ooperation

400W...700 W Ytterbium Fiber Blocks - IPG



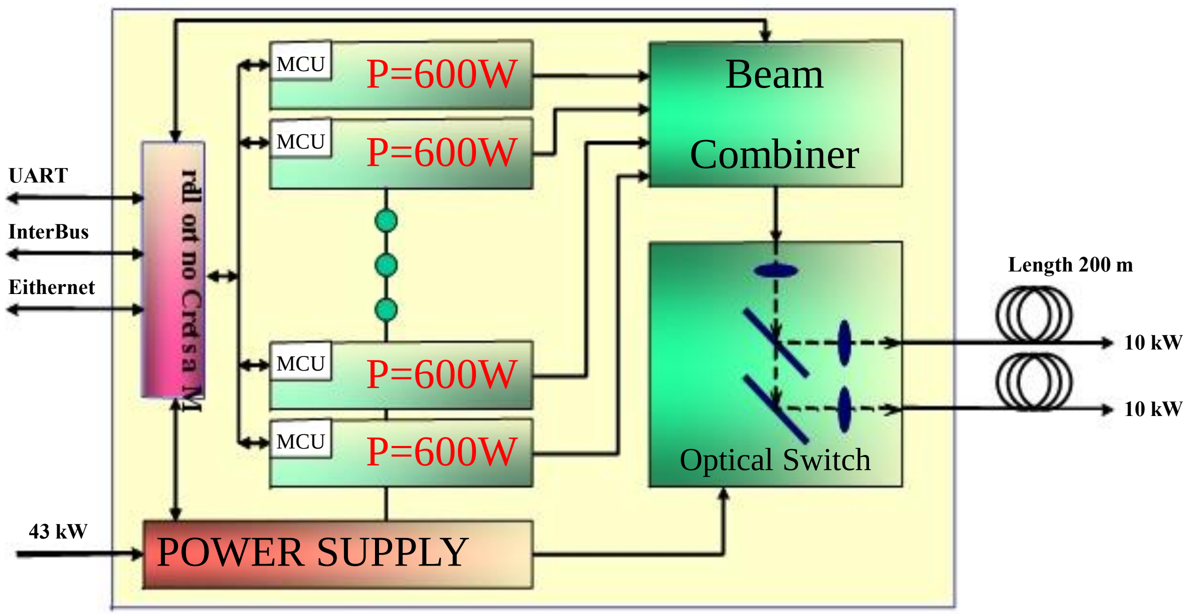
IPG Conception - IPG



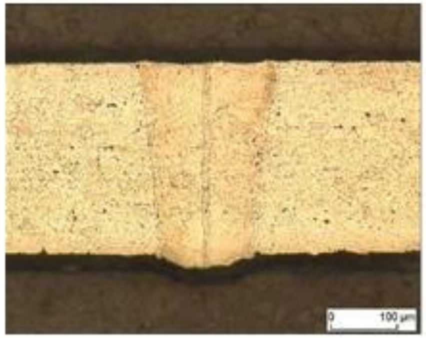
- Compact integrated optical design
- In parallel combining by single emitter diodes
- Side pumping
- Robust mechanical construction

kW-(multimode)-Fiber Lasers - IPG

YLR-10000: Block Diagram

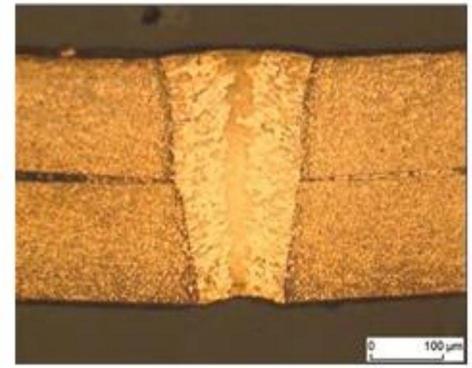


Welding with Singlemode-Fiber Lasers - IPG



Aluminium

Stainless steel



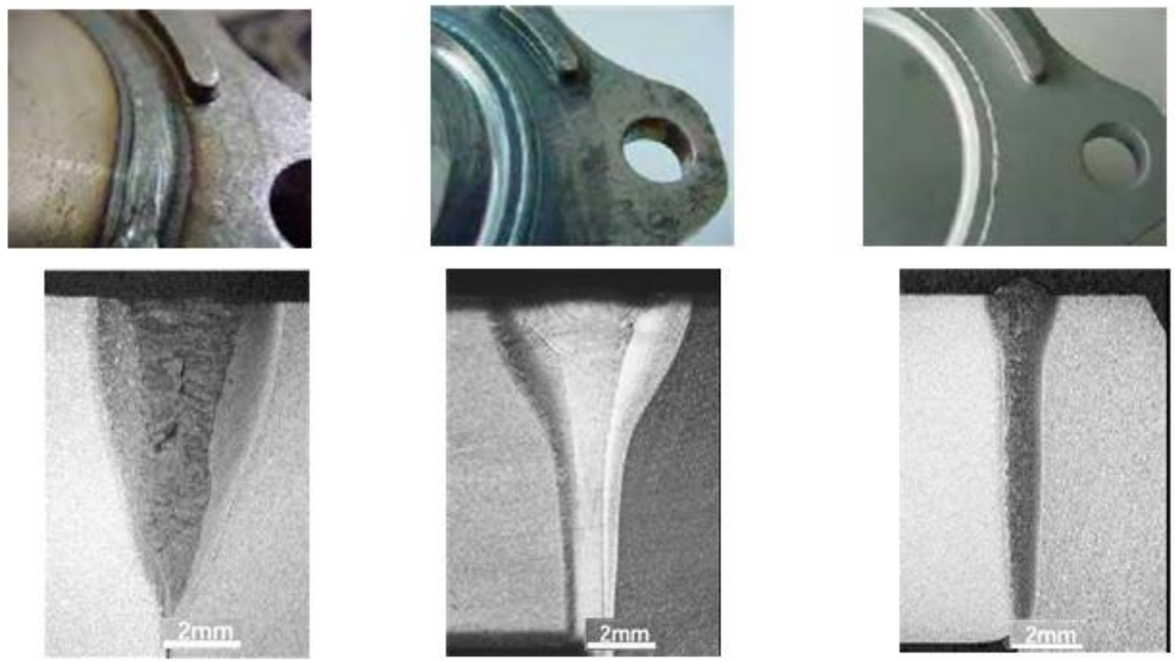
Copper

Fe-Cu-Joint

Welding of Gear Box Parts

Fraunhofer IWS Institut Werkstoff- und Strahltechnik

CO_2-Laser ***Electron beam*** ***Fiber Laser***

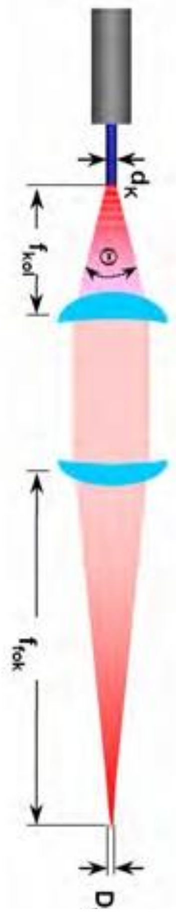


-Low heat input ⇨ Low distortion
-Reduced crack risk

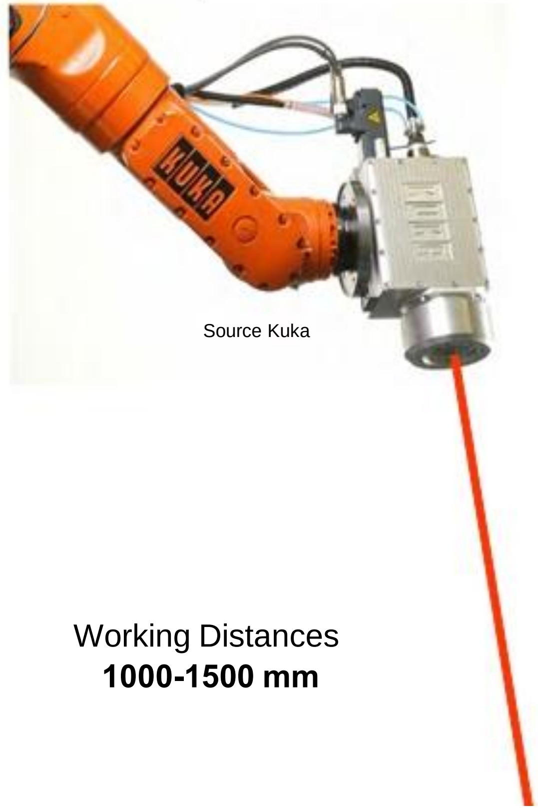
YLR4000-S

http://www.youtube.com/watch?NR=1&v=8B35zeYmeO4&feature=endscreen

Fiber Laser Remote Welding - IPG



***Scannerfree* Remote Processing**



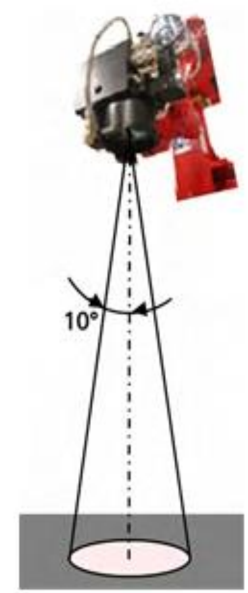
Source Kuka

Working Distances
1000-1500 mm

***Scanner* Remote Processing**

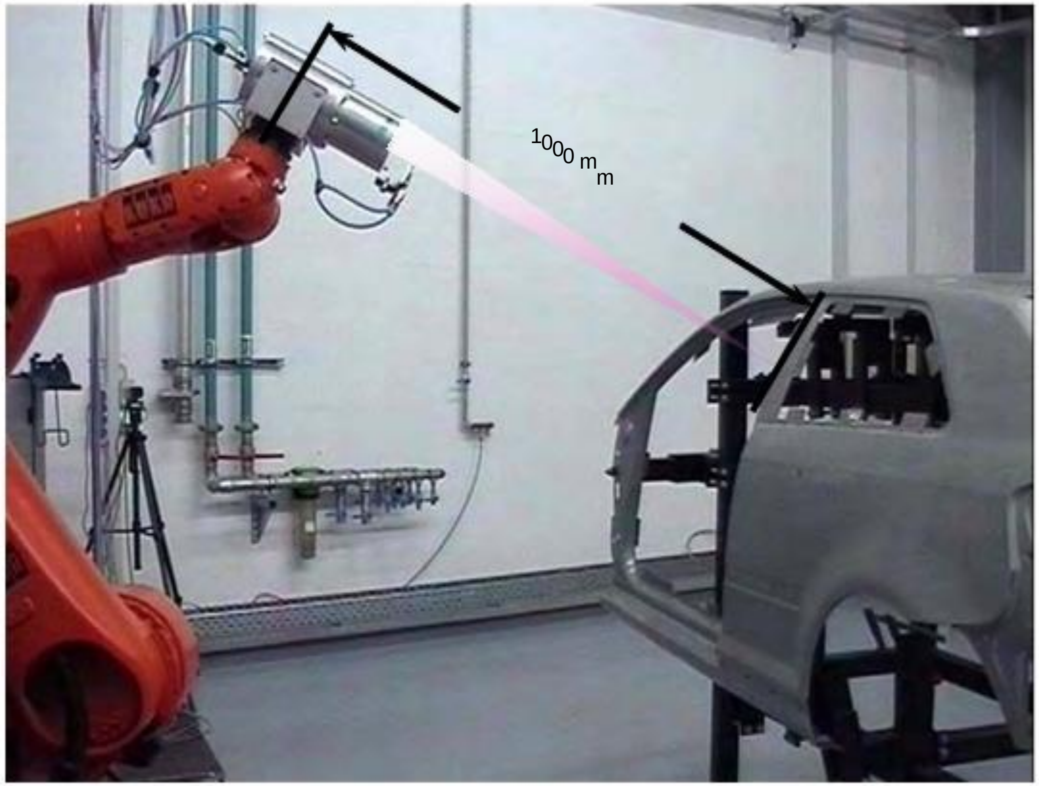
Source Highyag

Source IWS



Working Distances
~ 500 mm

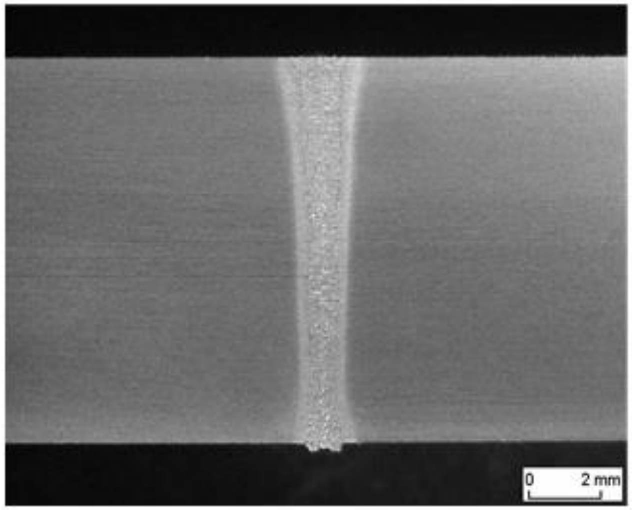
Remote Welding of Body in White (BIW)



High productive stitch welding for body in white

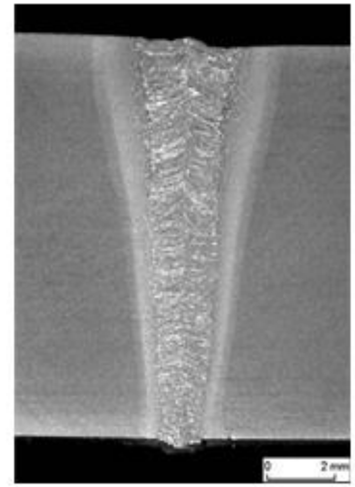
Process Efficiency

IPG YLR 10000 (10 kW Fiber Laser)



X70, t = 12 mm

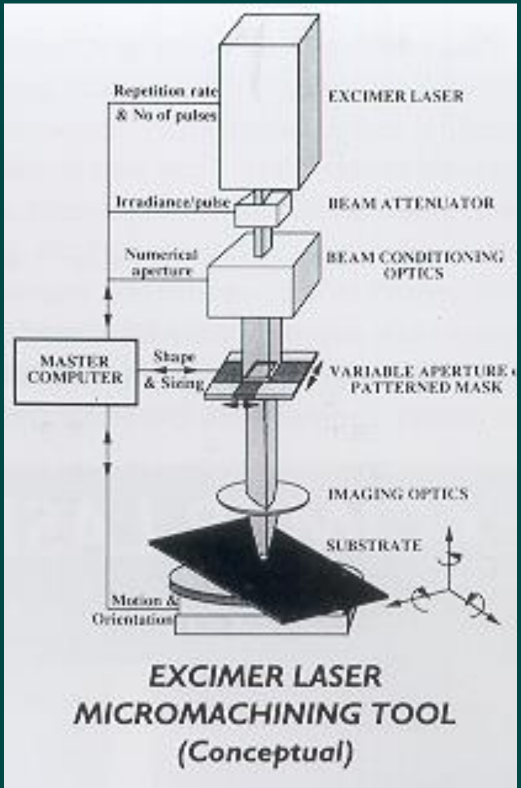
15 kW CO_2-Laser



X70, t = 12 mm

IPG YLR 10000		15 kW CO_2-Laser
P_L = 10.2 kW	+ 32 % →	P_L = 13.5 kW
v_W = 2.2 m/min	← +18 %	v_W = 1,8 m/min
E = 2,8 kJ/cm	+ 61 % →	E = 4,5 kJ/cm

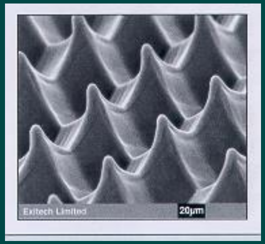
Excitech Lithographic Micro-machining System 8000



EXCIMER LASER MICROMACHINING TOOL (Conceptual)

Microstructures in polycarbonate

Mask projection



Mask dragging

KrF 248 nm wavelength
ArF 193 nm wavelength

Capable of machining PCB track widths 2 microns wide

CNC controlled and linked into CAD/CAM systems

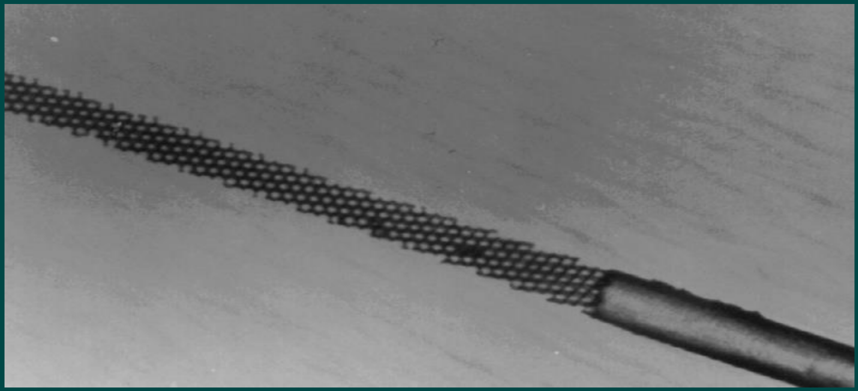
Structuring of most polymer, ceramic and glass materials

Precise etch depth control to 0.1 microns

Lateral resolution <0.5 microns

Volumetric material removal rate up to $1 mm^3/sec$

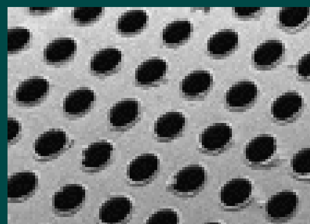
Example of Fine Processing With Excimer Lasers



- Hair diameter: ~50 microns (2 thou)
- Hole diameter: ~5 microns (0.2 thou)
- Illustrative of the resolution that can be achieved with a standard excimer laser using the mask-imaging technique and good quality beam delivery optics.

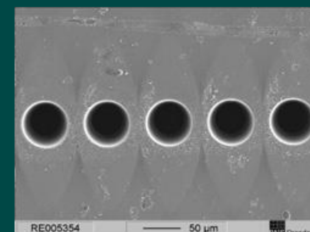
Excimer Laser Micro-Machining - Exitech

PCB Drilling



Printer Nozzles

720 dpi nozzle holes



Micro-Fluidic Systems

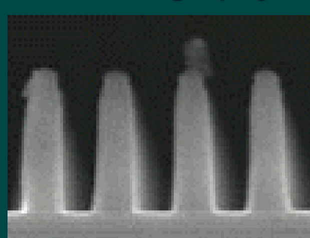
Biomedical Devices

Microstructuring

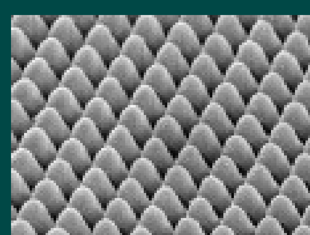
Fibre Gratings

Diamond Smoothing

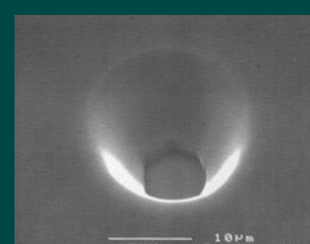
DUV Lithography



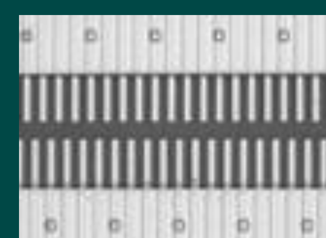
A-R Surface



Tapered micro-via

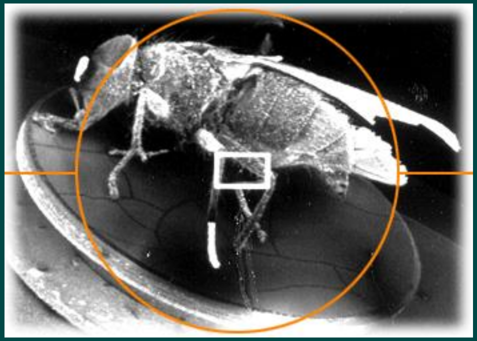


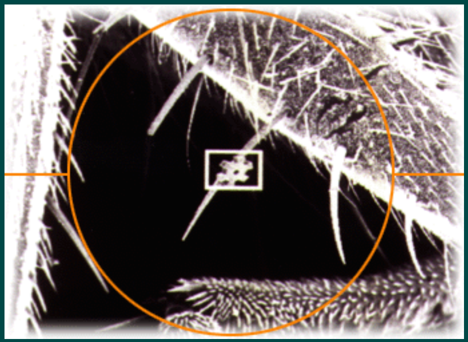
Sensors



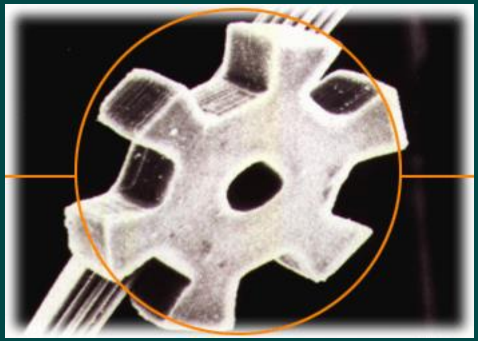
Excimer Laser Micromachining

http://www.youtube.com/watch?v=fFpov-ZSujA



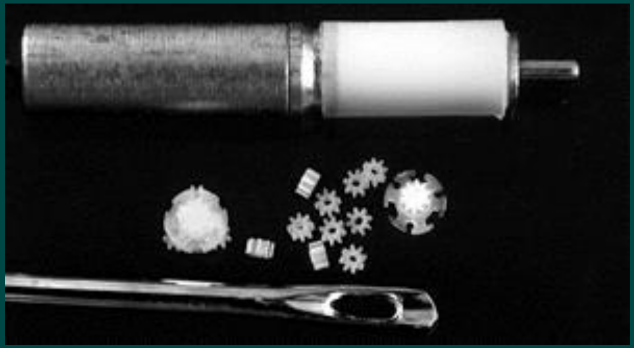


Gear 50 microns diameter



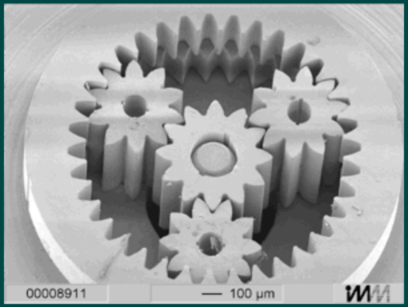
http://www.youtube.com/watch?v=GgR-mH6X5VU&feature=related

Micro-engineering Application

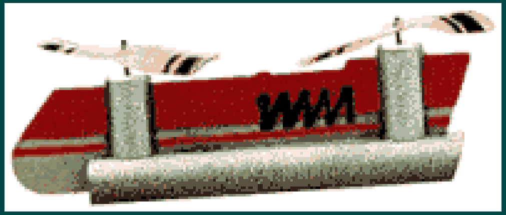


With a diameter of only 1.9 millimeters the electromagnetic motors can reach an incredible revolution speed of nearly 500,000 rpm.

They are also used for scanners, drive units in heart catheters and high-tech display systems.



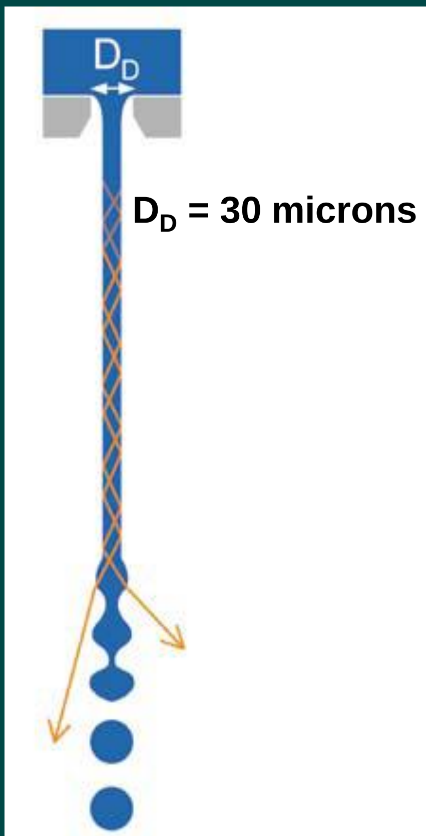
The integrated planetary gear system converts low torque at high rotational speed into high torque at correspondingly lower rotational speed.

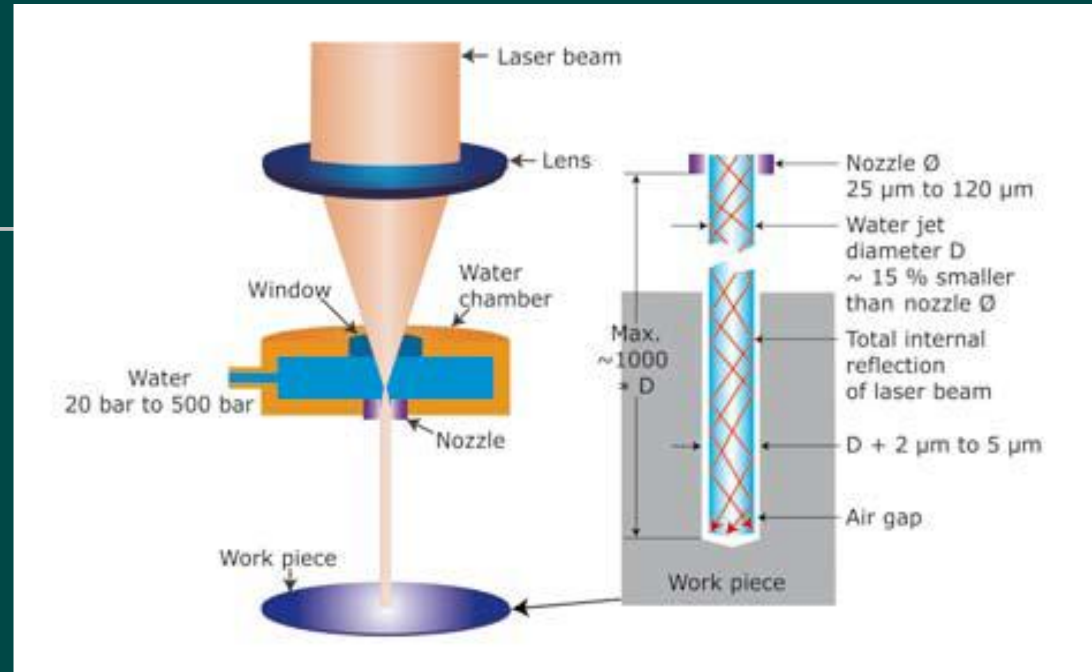


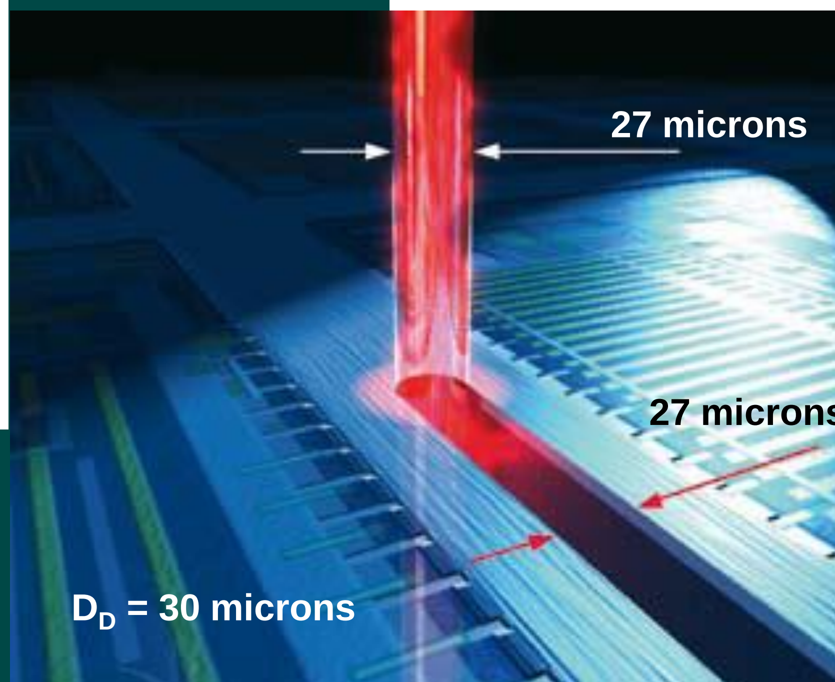
With a length of 24 mm and a weight of 0.4 grams the helicopter takes off at 40,000 rpm.

Institute of Microtechnology Mainz

Silicon Dicing

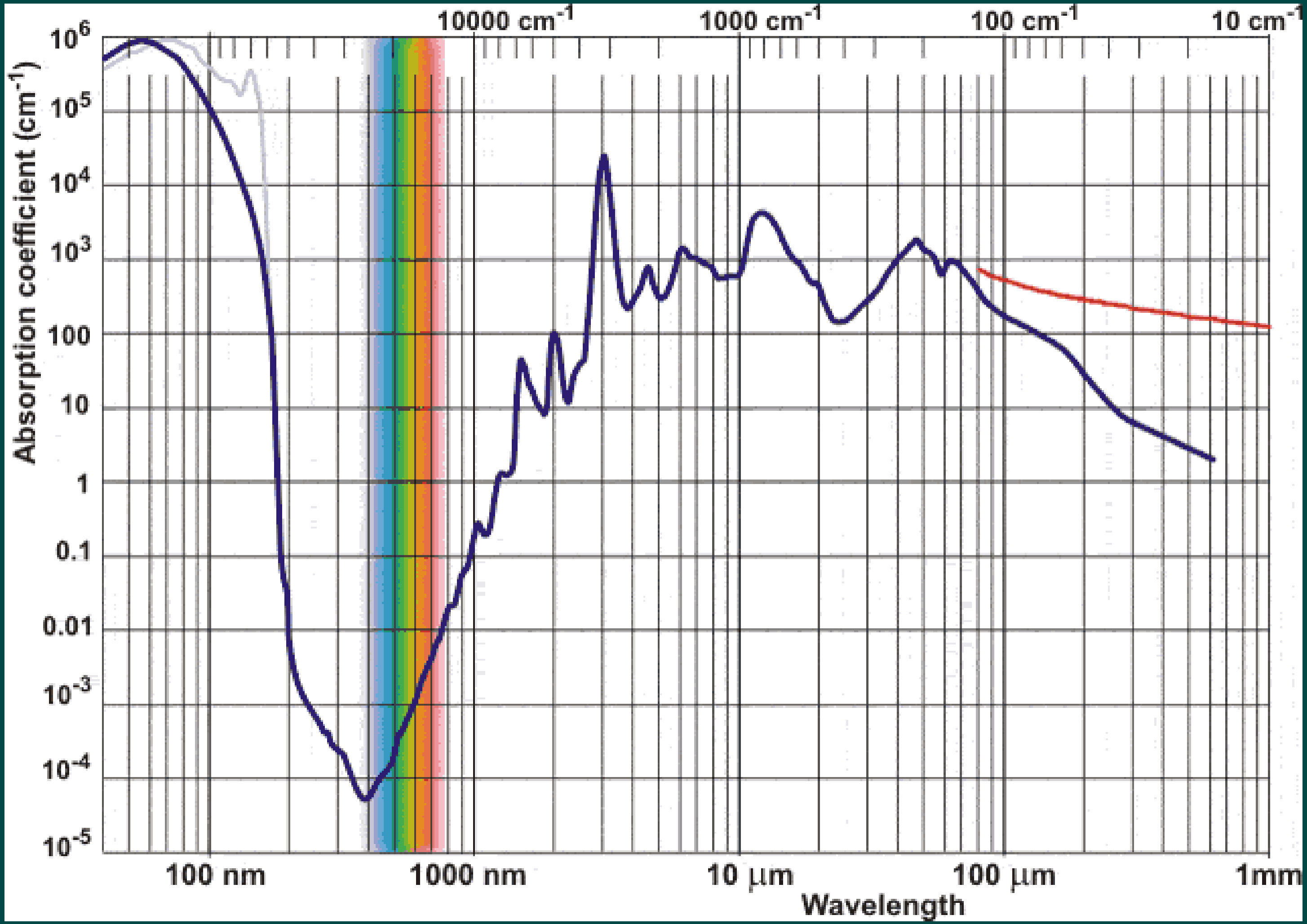




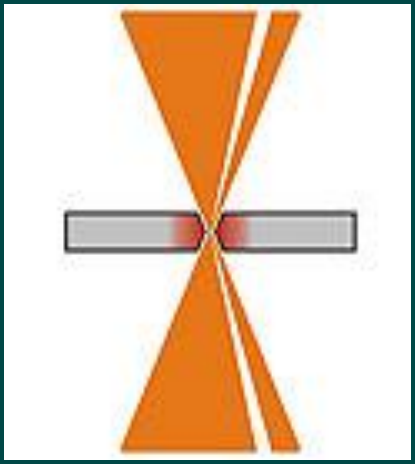


Nd-YAG laser pulsed micron and nano second pulses 532nm or 355nm wavelength, mean power 10 to 200watts

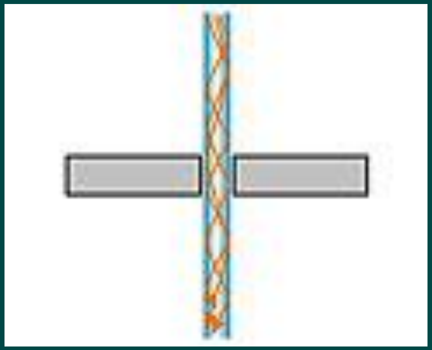
Water absorption coefficients



Laser Micro jet cutting



Conventional Process



Laser Micro jet Process

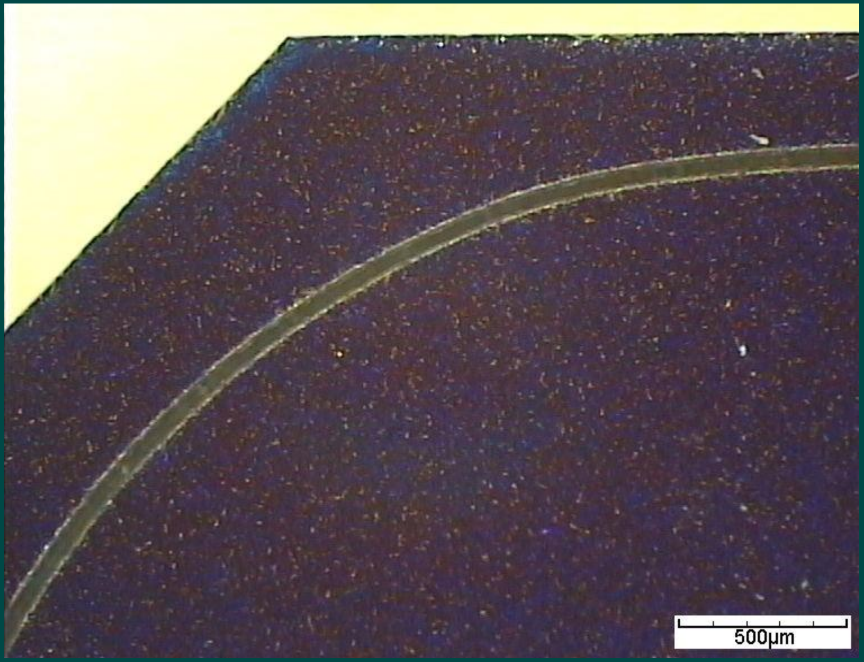
This machine can process silicon wafers up to 12" in diameter.

It can place cuts with 1 micron accuracy.

Curved cuts can be made as easily as straight cuts.

Photovoltaic (PV) Cell Edge Isolation

- In this example a rounded groove at the corner of the solar cell, something that a diamond saw cannot perform.
- The groove shown is ~ 20 µm deep, 40µm wide and was cut at a speed of 250 mm/s, with no post cutting cleaning required.



Blind and Micro-via drilling

Multi Laser (CO_2 /Nd: YAG)

Drills both copper and dielectric

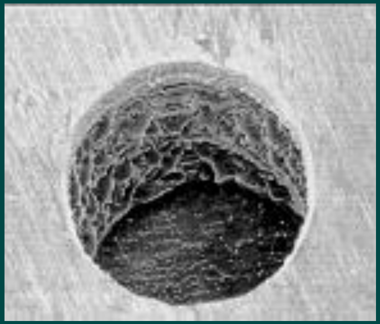
High speed - up to 60,000 holes/minute

The pulsed frequency trippled 3Watt YAG (355nm) laser is used for drilling metals

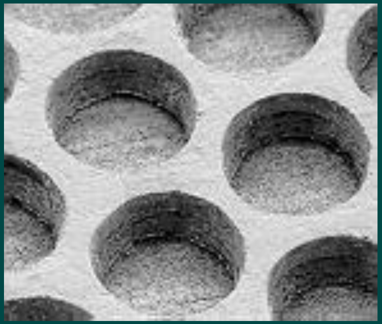
A wavelength tuned pulsed 80 Watt CO_2 (9.6 microns)laser is used for removal of dielectric

High speed drilling of blind and microvias in all types of multilayer printed circuit boards (PCB's), and multichip modules (MCM's) for panel sizes up to 24" x 28".

Blind and Micro-via drilling

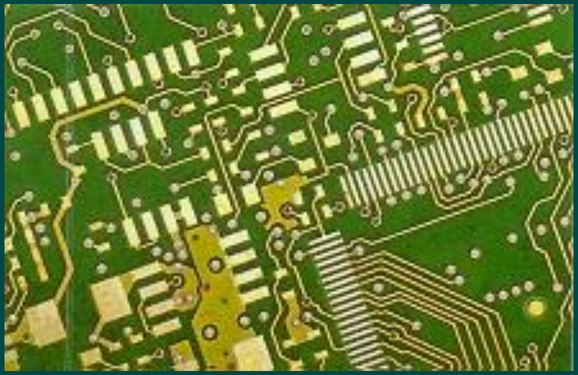


200 μm blind via - 18μm top copper - 125 μm FR4 - laser cleaned bottom copper

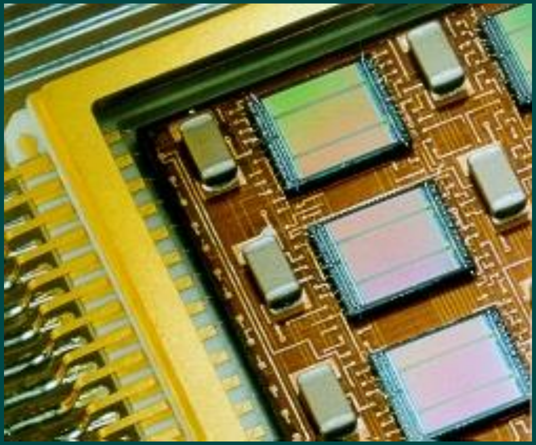


Array of 125 μm blind vias in 25 μm polyimide - pre-patterned top copper

Through holes and annular rings

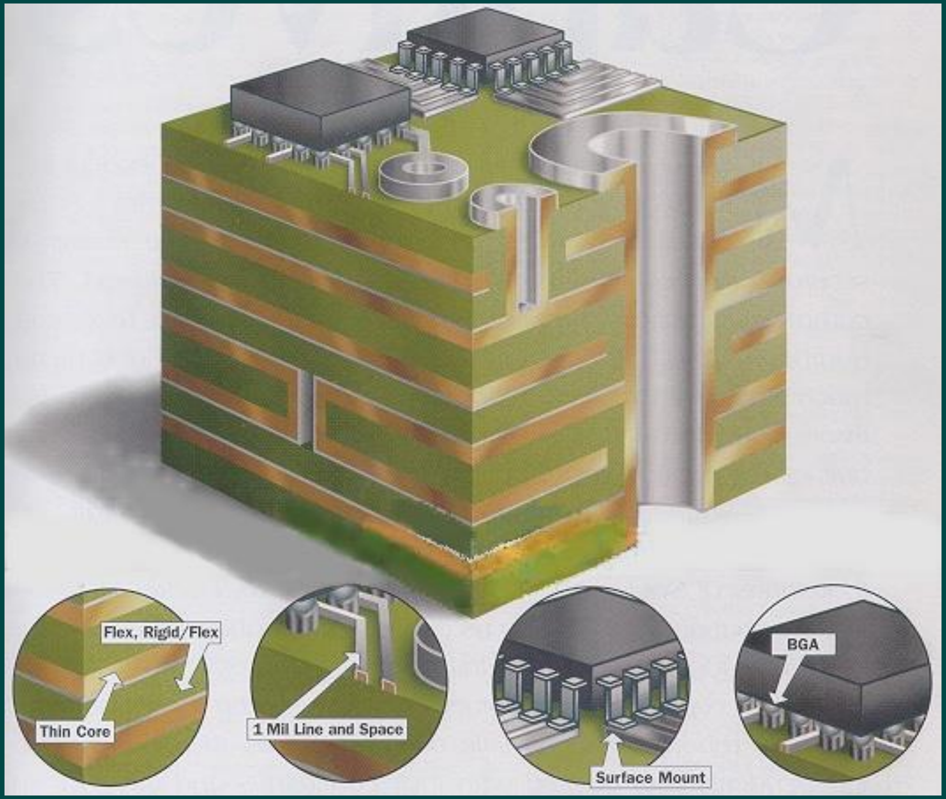


Circuit board blind vias

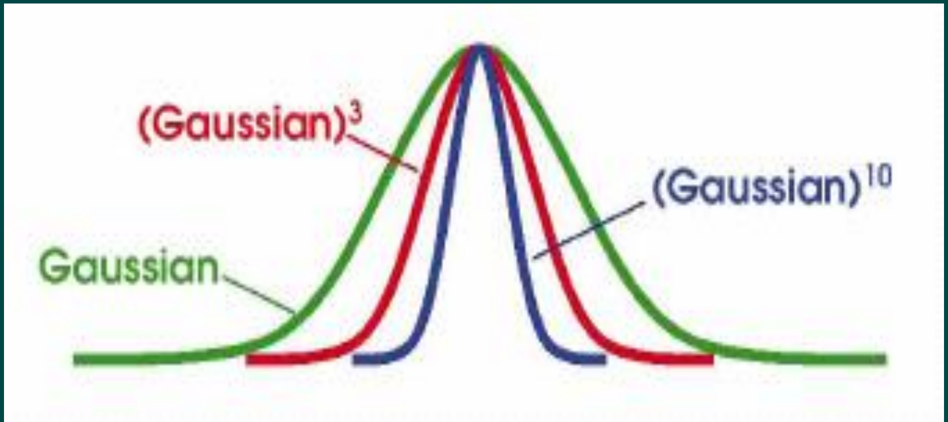


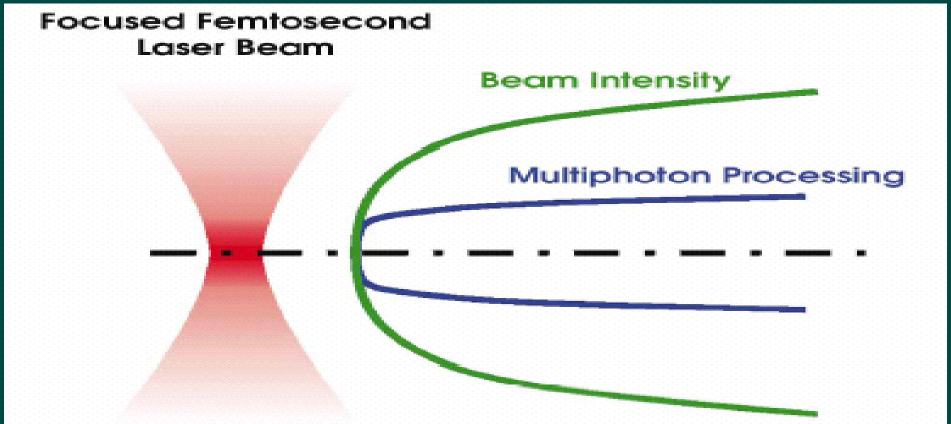
25 μm blind vias

Miniaturised Electronic Products



Femtosecond Laser Beam Characteristics

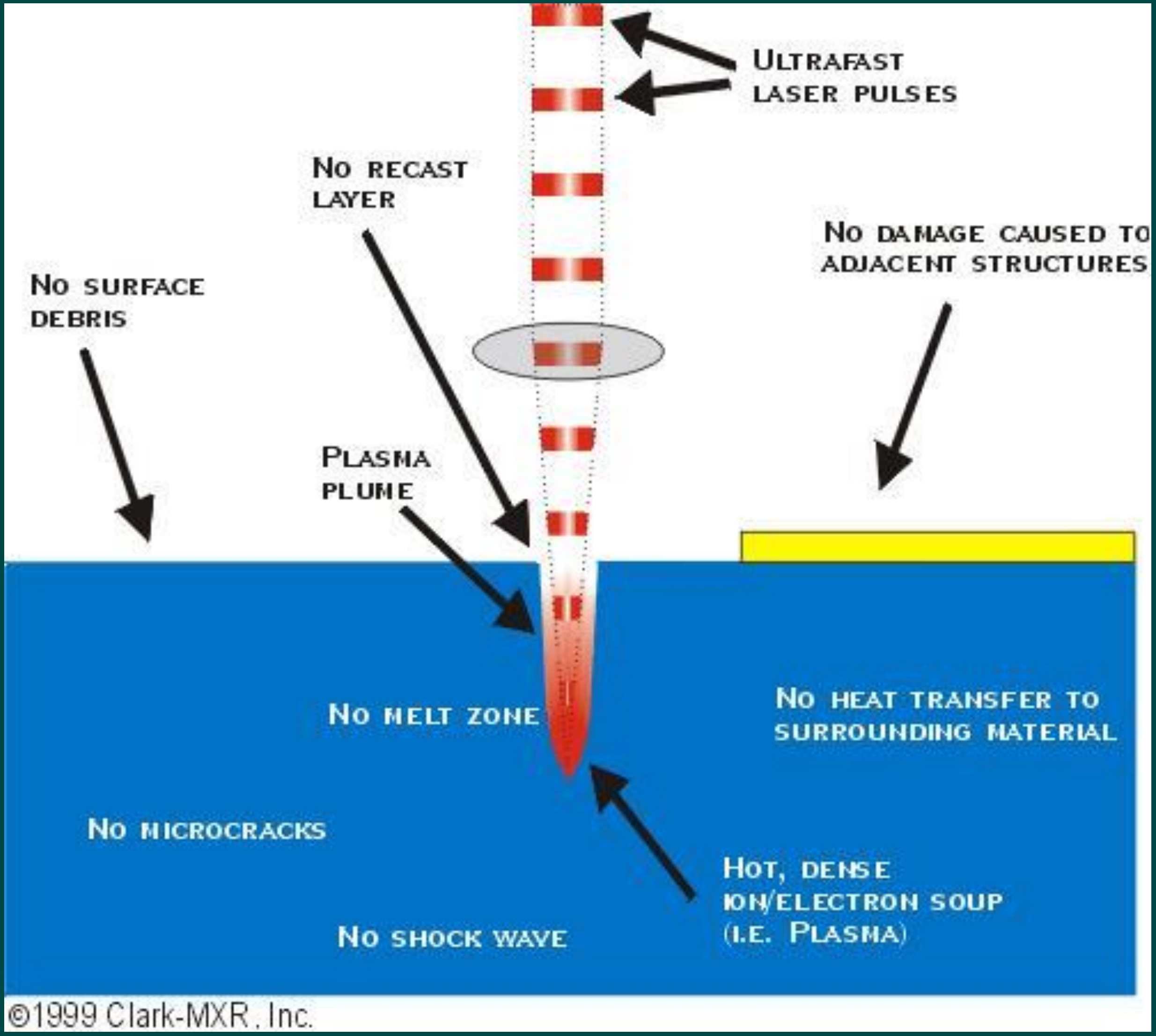




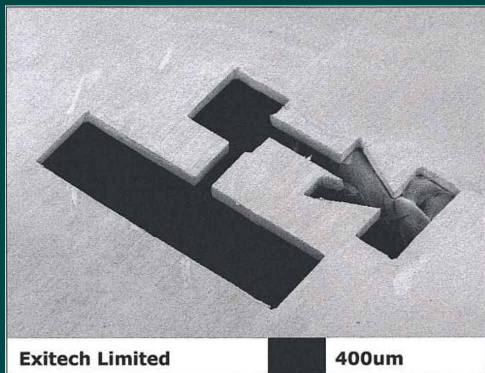
Ti:sapphire lasers with output centred at 800nm have the ability to machine features as small as 70nm. With multi photon absorption, laser power scales as (laser power)^N where N is the number of photons simultaneously absorbed. N ranges from 3 to 10.

Courtesy of Marco Arrigoni - Coherent

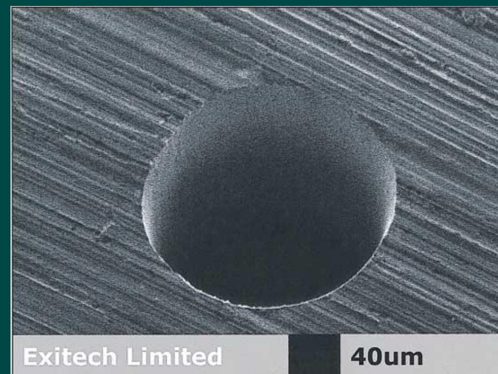
Ultra Fast Pulse Interaction



Femtosecond Laser Machining Ti:sapphire - Exitech

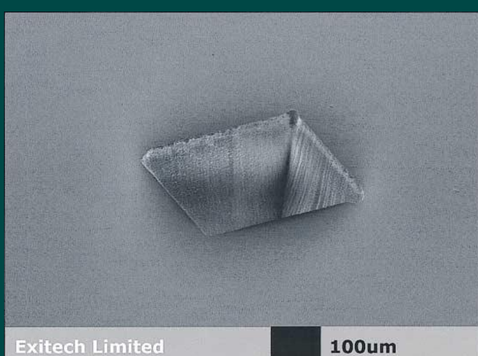


Aluminium

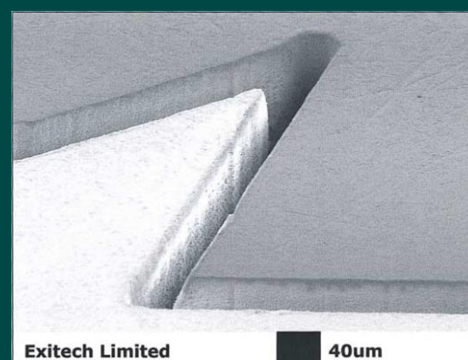


Stainless Steel

100 micron diameter hole drilled in stainless steel using a 355 nm nanosecond pulse Nd: vanadate laser



Silica

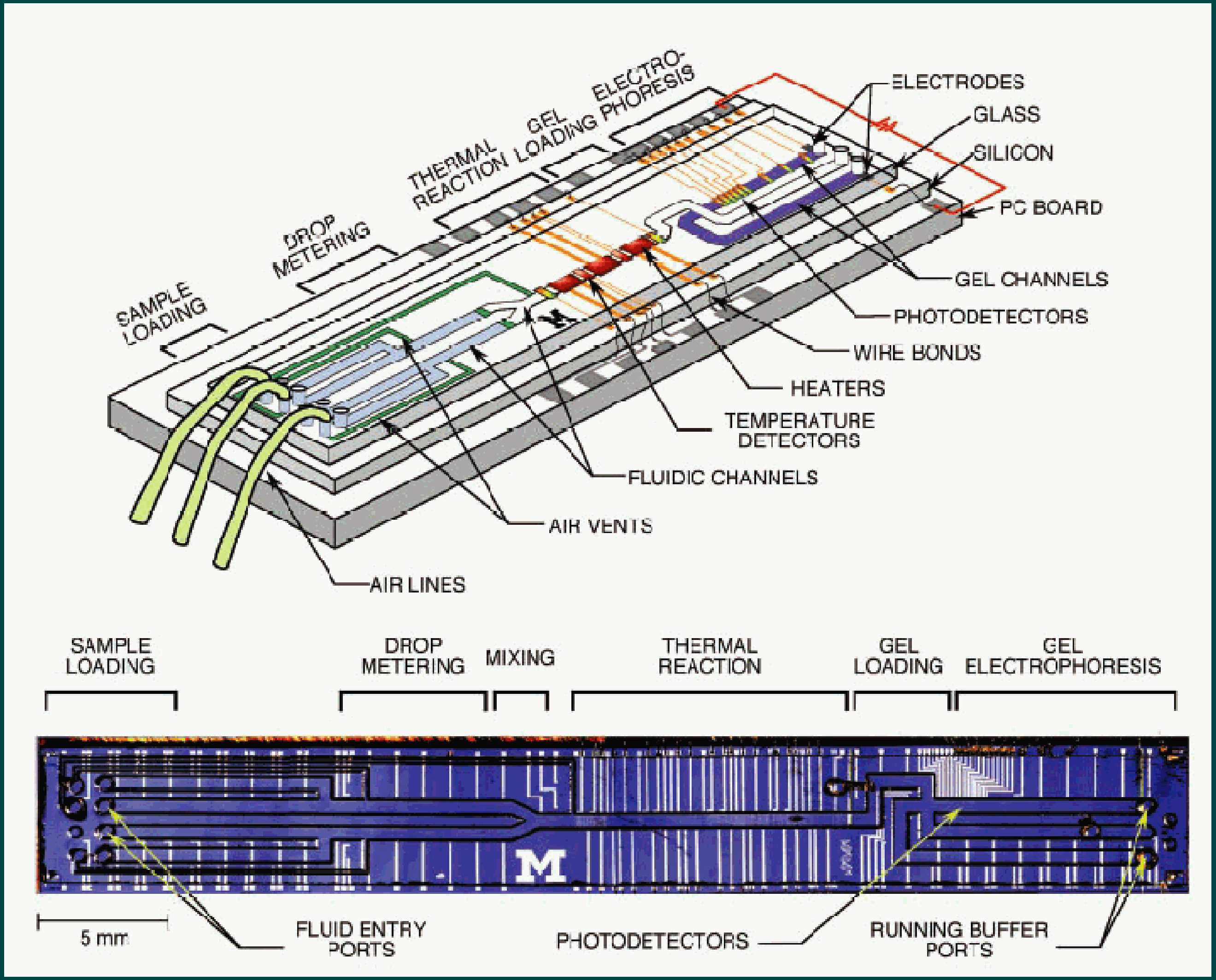


Glass

Lithium Tantalate

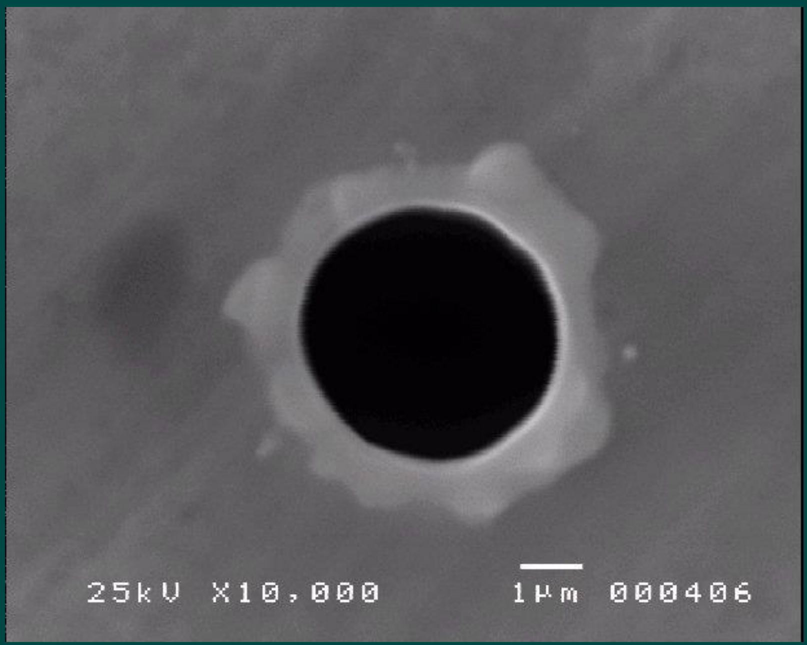
Ti:sapphire laser; λ_0 = 800 nm, $\Delta\tau$ = 110 fs,
E =1mJ/pulse, Rep Rate=3–5kHz, $M2$ =1.2

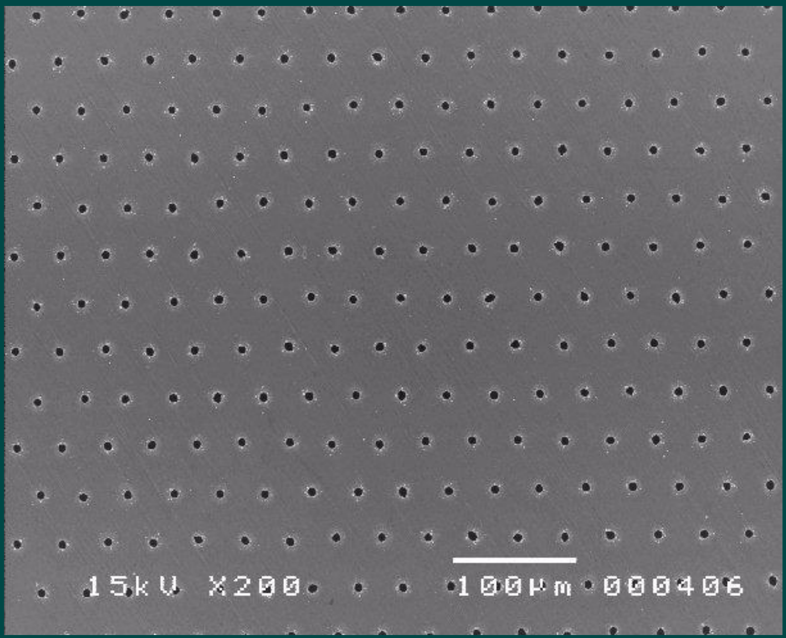
Lab on a Chip



SAMPLE LOADING
DROP METERING
THERMAL REACTION
GEL LOADING
ELECTRO-PHORESIS
ELECTRODES
GLASS
SILICON
PC BOARD
GEL CHANNELS
PHOTODETECTORS
WIRE BONDS
HEATERS
TEMPERATURE DETECTORS
FLUIDIC CHANNELS
AIR VENTS
AIR LINES
SAMPLE LOADING
DROP METERING
MIXING
THERMAL REACTION
GEL LOADING
GEL ELECTROPHORESIS
5 mm
FLUID ENTRY PORTS
PHOTODETECTORS
RUNNING BUFFER PORTS

Precision Percussion Drilling of Stainless Steel - Copper Vapour Laser – Oxford Lasers





Photograph shows a 22,000 hole array of 5μm diameter holes. Material is stainless steel, 100 μm Copper Vapour Laser , 511 & 578 nm, 10kHz, 20 to 30 ns pulses, 50 to 500 kW

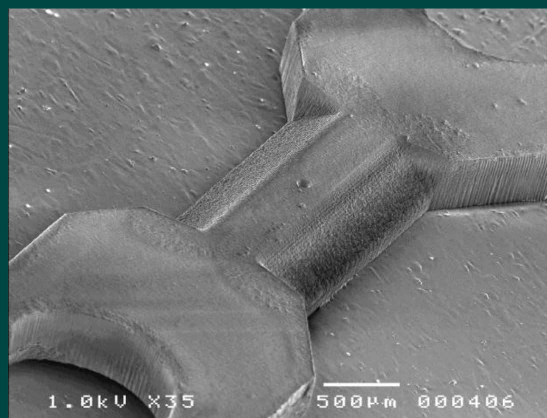
CVL Hole Drilling Capability Table
Oxford Lasers

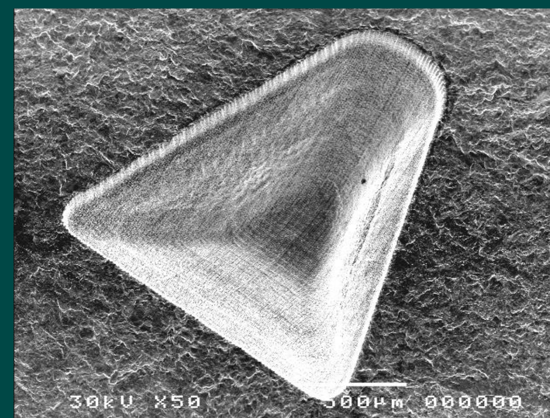
Diameter – laser exit side (*µm*)	Taper (*µm)*	Thickness (*µm)*	Exit Side Diameter Tolerance (*µm)*
1.5 – 15	+ (5 – 10)	10 – 100	+/- 1
15 – 500	+ (5 – 10)	10 – 200	+/- 0.25 to +/- 1.5
40 – 500	+10 to 0 to -10	200 – 1000	+/- 2 to +/- 4

Nanosecond Pulse Ablation : Micro-Milling

Examples of optimized processes with nanosecond laser sources

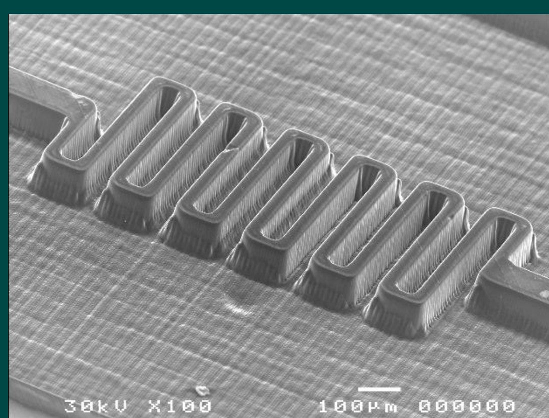
Alumina
511nm

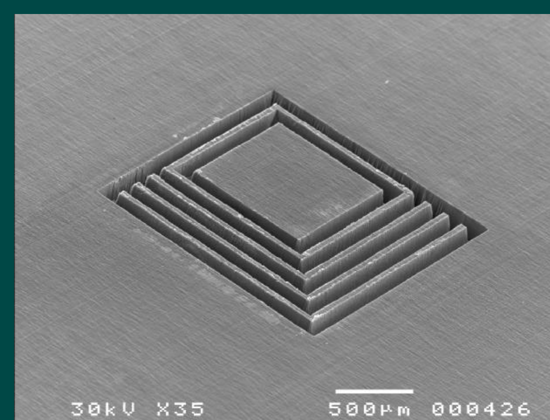




Tungsten
511nm

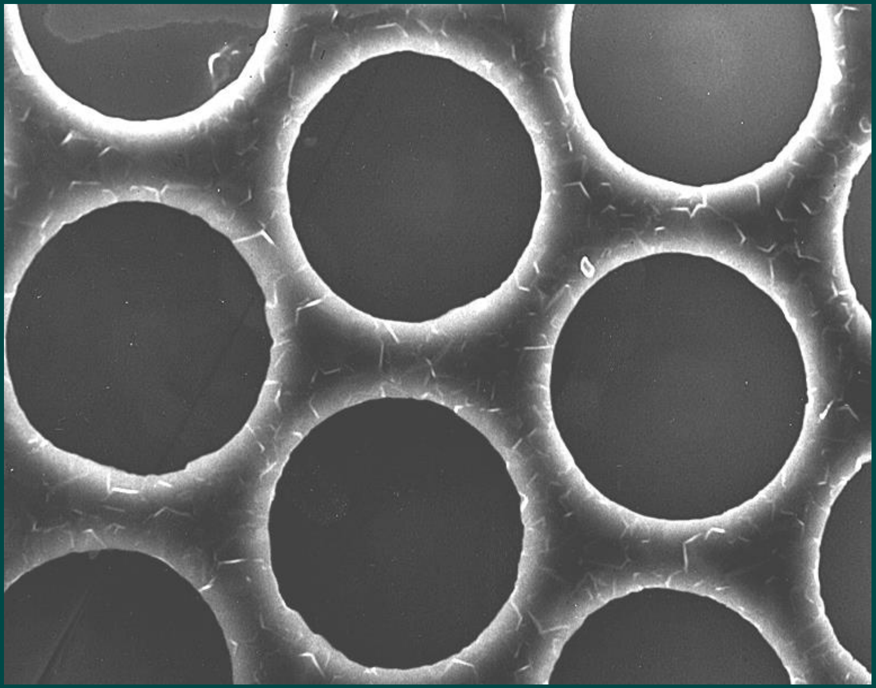
Diamond
511nm





Polyimide
355nm

Precision Holes in CVD Diamond – CVL
(Sample grids for Transmission Electron Microscopes)



Photograph: An array of precision drilled holes of 230µm diameter on a 295µm pitch in 250 µm thick synthetic diamond.

(Photograph courtesy of GEC-Marconi, Materials Technology Ltd,

The End